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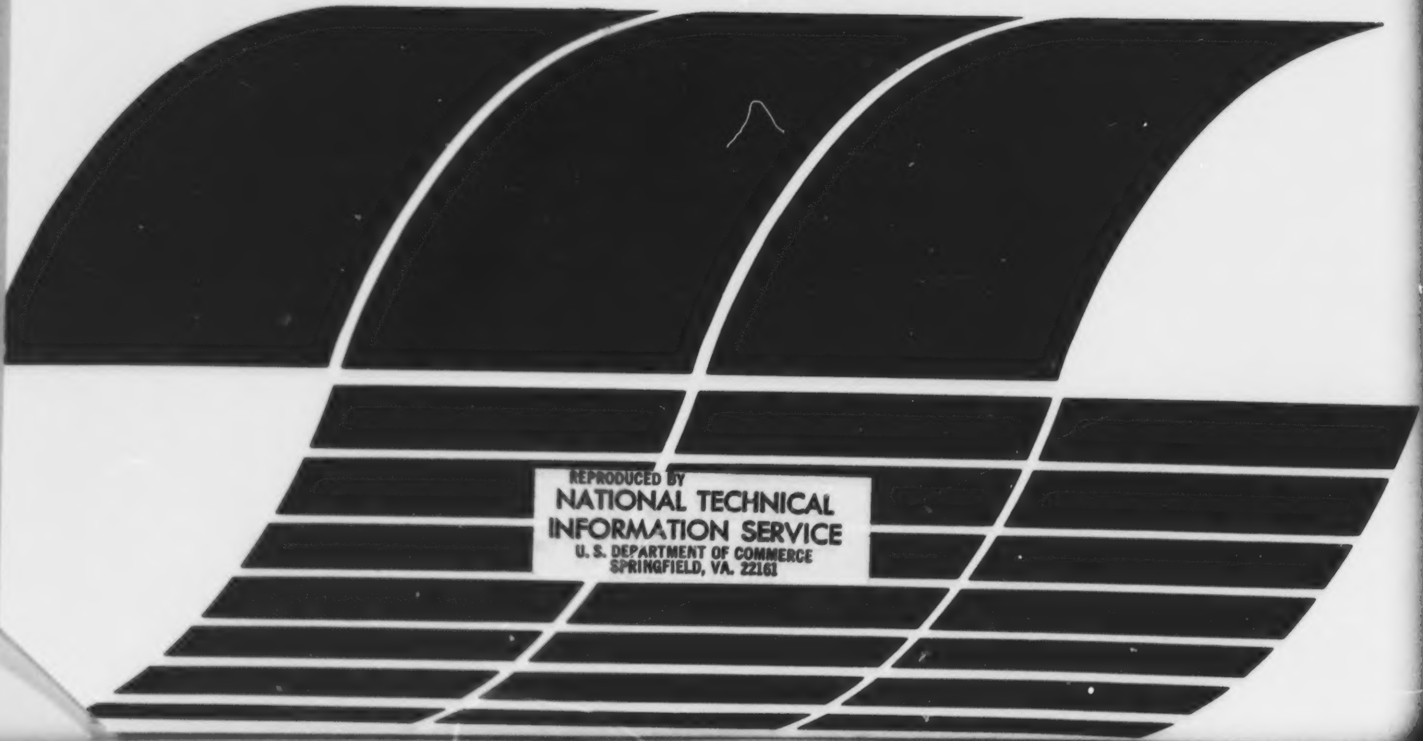

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Estimates of energy requirements for pollution control at stationary sources in the United States, as compiled from the literature, are presented and discussed. The data are analyzed to determine the distribution of energy requirements among economic sectors and among pollutant types. Alternative methods of pollution control that are potentially less energy intensive and still capable of meeting environmental regulations are also discussed.

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FOREWORD

When energy and material resources are extracted, processed, converted, and used, the related pollutional impacts on our environment and even on our health often require that new and increasingly efficient pollution control methods be used. The Industrial Environmental Research Laboratory - Cincinnati (IERL-Ci) assists in developing and demonstrating new and improved methodologies that will meet these needs both efficiently and economically.

Recent fuel shortages have given rise to questions concerning the compatibility of national goals for a clean environment with goals for energy self-sufficiency. These questions have in turn given rise to a growing number of studies related to the energy cost of pollution control.

This report attempts to summarize and integrate the available results of these studies to obtain the broadest, most accurate perspective possible on how the problem relates to stationary sources of environmental pollution. The results will be used by the Office of Research and Development of the U. S. Environmental Protection Agency to identify areas where improvements in the energy efficiency of present methods of pollution control are most important and the alternatives that are available for effecting such improvements. The information contained in this report will also be of interest as background material to researchers and administrators involved with environmental control. The Power Technology and Conservation Branch of the Energy Systems Environmental Control Division should be contacted for additional information.

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Industrial Environmental Research Laboratory
Cincinnati

ABSTRACT

The results of a 500-staff-hr, quick-response, task-order study are presented here. The objectives were 1) to summarize and evaluate available information on the energy required for stationary source pollution control and 2) to identify potential areas and methods for reducing these energy requirements.

The following stationary sources were considered on a multimedia (air, water, and land) basis: electric power plants, industrial sources, municipal wastewater treatment plants, and municipal solid waste disposal systems.

This report was submitted in fulfillment of Contract 68-02-1331, Task 22 by Monsanto Research Corp. under the sponsorship of the U.S. Environmental Protection Agency. This report covers a period from March 4, 1976, to June 30, 1976, and work was completed as of December 31, 1977.

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ENGLISH TO METRIC CONVERSION FACTORS[a]

To convert from	To	Multiply by
Barrel (42 gallons)	Meter^3	0.1589
British thermal unit	Joule	1,055
Degree Fahrenheit	Kelvin	$t_{°K} = 273.15 + (t_{°K} - 32)/1.8$
Foot	Meter	0.3048
Foot^3	Meter^3	0.02831
Foot^3/minute	Meter^3/second	4.719×10^{-4}
Gallon (U.S. liquid)	Meter^3	0.003785
Horsepower	Watt	746.0
Kilowatt-hour	Joule	3.60×10^{6}
Pound mass	Kilogram	0.4536
Quad	Joule	1.06×10^{18}
Ton (short, 2,000-pound mass)	Kilogram	907.1

[a] Standard for Metric Practice. ANSI/ASTM Designation: E 380-76^{ε}, IEEE Std 268-1976, American Society for Testing and Materials, Philadelphia, Pennsylvania, February 1976. 37 pp.

SECTION 1

INTRODUCTION

The present and projected shortages of domestic, environmentally clean fossil fuels coupled with the cost and uncertainty of importing foreign fossil fuels have provided economic and political incentives to conserve energy at all levels of the U.S. economy.

This report is concerned with the energy required for pollution control at the following stationary sources: electric powerplants, industrial sources, municipal wastewater treatment plants, and municipal solid waste disposal sites.

The report is divided into three major parts. First, in Section 4, data on energy requirements for pollution control obtained from a literature survey are summarized and critically reviewed. Energy requirements are given both on a nationwide basis and on a process or unit basis. In Section 5, the available data are analyzed to determine the distribution of pollution control energy requirements among stationary source sectors, pollutant types, and industrial source categories. Potential methods for reducing pollution control energy requirements while still meeting environmental regulations are considered in Section 6. The results of this study are summarized in Section 2.

Generally speaking, the energy requirements for pollution control given in this report can be interpreted as energy required to meet all currently enacted Federal regulations after the legal granting of exemptions has been taken into account. However, studies reported in the literature are not entirely consistent as to which regulations are assumed to be met.

The energy requirements given in Sections 4 and 5 are also based on the use of presently available control technology. The term "presently available" generally refers to current practice and/or extrapolations of current trends; it does not mean the most energy-efficient control possible with today's technology. Thus alternatives to presently available methods do not necessarily involve new technology.

SECTION 2

SUMMARY OF RESULTS

The total energy required to meet government regulations for pollution control at stationary sources in the United States in 1977 is 1.7 quad[a], with estimated error bounds of 0.8 quad to 3.4 quad. This emount of energy represents approximately 2% of total U.S. energy consumption, with a range of approximately 1% to 4%. These values represent operating energy only; an additional 0.2 quad would be required for fabrication and installation of pollution control equipment. Projections for the mid-1980's indicate that the percentage energy requirement for stationary source pollution control will increase only slightly to between 2.5% and 3% of total U.S. energy consumption in 1985.

The 1977 energy requirements for pollution control are distributed among stationary source sectors as follows: industry, 58%; powerplants, 20%; municipal wastewater treatment plants, 16%; and municipal solid waste disposal, 6%. Of the energy required for pollution control in the industrial sector, approximately 80% is concentrated in the following industrial categories:

- Primary metals
- Chemicals and allied products
- Paper and allied products
- Petroleum and coal products
- Fabricated metal products
- Stone, clay, and glass products
- Food and kindred products

The primary metals category alone accounts for 36% of the industrial total. The iron and steel industry accounts for approximately 70% of the total pollution control energy requirement in the primary metals category; this represents 25% of the energy requirement in the industrial sector and 15% of the energy requirement for pollution control at all stationary sources.

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[a] One quad = 10^{15} Btu = 1.06×10^{18} J. The energy values quoted in this section represent primary thermal energy (see Section 4). Because of the pervasive use of Engligh units to express energy values in the United States, these units are used in this report to facilitate interpretation of data. An English-Metric conversion table is given on Page v.

The 1977 energy requirements for stationary source pollution control are distributed among pollutant types as follows: water (chemical and biological), 36%; sulfur oxides (SO_x), 33%; particulate matter, 10%; thermal pollution, 9%; other air pollutants [nitrogen oxides (NO_x), hydrocarbons, carbon monoxide (CO)], 6%; municipal solid waste, 6%. Thus, chemical and biological water pollution control and control of SO_x emissions account for about 70% of the total pollution cntrol energy requirement.

A number of potentially less energy-intensive alternatives to present pollution control practices are summarized in Table 1. Consideration is restricted to those methods that could have a significant impact in the period 1985 to 1990.

TABLE 1. LESS ENERGY-INTENSIVE POLLUTION CONTROL ALTERNATIVES

Pollutant controlled	Alternative
Sulfur oxides	Fluidized-bed combustion of coal.
	Intermittent control systems (fuel switching, load shifting, tall stacks).
	Coal blending.
	More energy-efficient scrubbers.
Thermal pollution	Spray ponds and cooling ponds as opposed to cooling towers.
	Waste heat utilization (for space heating or wastewater treatment, for example).
Municipal and/or industrial wastewater	Recovery of sludge digester gas.
	Trickling filter as opposed to activated sludge for secondary treatment.
	Solvent regeneration of activated carbon.
	Reverse osmosis, electrodialysis, and vapor compression evaporation for concentration of wastewater streams.
Municipal solid waste	Energy recovery via pyrolysis or incineration.
	Recycling of metals, glass, paper.
	Improved packaging techniques.
Industrial air and water pollution	Process modifications to reduce number and size of streams requiring end-of-pipe treatment.

Intermittent systems for SO_x control at combustion sources are designed to meet ambient air quality standards and are not capable of meeting all regulations. Other methods of SO_x control, such as oil desulfurization, coal cleaning, and substitution of low-sulfur western coal, are at least as energy intensive as flue gas scrubbing. Thus fluidized-bed combustion (FBC), coal blending, and more energy-efficient scrubbers represent the main opportunities for near-term reduction of energy requirements for SO_x control.

First-generation, fluidized-bed powerplants (now in the demonstration phase) are expected to have overall thermal efficiencies comparable to conventional plants equipped with scrubbers. However, later-generation FBC systems are projected to have significantly higher efficiencies. The greatest potential energy savings are in electric powerplants and large industrial boilers, for which pressurized FBC (as opposed to atmospheric FBC) is likely to be economical. Another advantage of FBC is that NO_x emissions are also controlled, so future NO_x standards would be met without an additional energy penalty.

The blending of low-sulfur western coal with high-sulfur coal to meet SO_x emission standards requires about one-fourth the energy required for flue-gas scrubbing. By comparison, complete substitution of low-sulfur western coal for high-sulfur eastern coal requires approximately the same amount of energy as does flue-gas scrubbing.

Spray ponds and cooling ponds are about one-half as energy intensive as forced-draft cooling towers for thermal pollution control. Natural-draft cooling towers are a less energy-intensive alternative for industrial sources, but they would save only about one-sixth of the energy saved by installing spray ponds or cooling ponds. These methods have the drawbacks of large land requirements and capital investment costs.

The waste heat rejected from electric powerplants and industrial processes represents a substantial energy resource. It is estimated that use of waste heat from electric powerplants for space heating could save up to 5 quads annually in the United States. Thus integrated systems for the utilization of waste heat in space heating, agriculture, aquaculture, sewage treatment, etc., represent the least energy-intensive method of thermal pollution control.

The energy required for municipal or industrial wastewater treatment could be reduced through utilization of the gas produced by anaerobic digestion of organic sludge. Sludge digester gas can be used to fuel internal combustion engines, which can be directly coupled to air blowers and water pumps; or the gas can be used to drive electrical generators. It is estimated that all of the electrical energy requirements for primary treatment plants, or approximately two-thirds of electrical energy requirements for activated sludge plants, could be supplied in this manner. For secondary wastewater treatment, trickling filter plants require up to 50% less energy than activated sludge plants.

Solvent regeneration of activated carbon used for advanced wastewater treatment may require only one-tenth the energy required for thermal regeneration. Reverse osmosis, electrodialysis, and vapor compression evaporation are less energy-intensive alternatives to standard multieffect evaporation for the concentration of wastewater streams.

Energy recovery via incineration or pyrolysis of municipal solid waste constitutes a much less energy-intensive alternative to landfilling. Most processes for energy recovery are in the development or demonstration stages. However, waterwall incinerators constitute a proven technology with a high energy recovery efficiency.

Recovery and recycling of scrap metals, paper, and glass in solid waste is also less energy intensive than landfilling these materials.

Reduction of per capita consumption of packaging materials through improved packaging techniques would save energy by reducing the solid waste load and by reducing the amount of packaging material produced. Potential total energy savings are estimated to be 0.6 quad/yr, approximately six times the energy required for landfilling municipal solid waste in the United States.

One method of reducing energy requirements for industrial pollution control is process modification to reduce the number and size of streams requiring end-of-pipe treatment. This technique is difficult to deal with in general terms since modifications are usually process-specific and often plant-specific. However, process modifications could result in substantially lower pollution control energy requirements than those projected for the industrial sector based on end-of-pipe treatment alone.

SECTION 3

CONCLUSIONS

Analysis of data obtained from the literature leads to the following conclusions:

- The energy required to meet government regulations for pollution control at stationary sources in 1977 amounts to about 2% of total U.S. energy consumption, with a range of approximately 1% to 4%. Projections for the mid-1980's indicate that this figure will increase only slightly to between 2.5% and 3% of projected total national energy consumption.

- Pollution control in the industrial sector accounts for approximately 60% of energy requirements for control at stationary sources. Energy requirements are concentrated in the following industrial categories: primary metals, chemicals, paper and paper products, and petroleum and coal products.

- Industrial and municipal wastewater treatment and control of SOx, primarily from industrial and utility boilers, account for approximately 70% of the energy required for control at stationary sources. Hence efforts to reduce energy requirements for stationary source pollution control should be directed most heavily toward these two areas.

SECTION 4

SUMMARY AND EVALUATION OF PREVIOUS WORK

Results obtained from the literature survey are summarized and evaluated in this section. The results are divided into three categories: 1) operating energy required for pollution control on a national basis, 2) energy required for fabrication and installation of pollution control equipment on a national basis, and 3) energy required for pollution control on a process or unit basis. An overview of the literature survey is presented in Appendix A, where each study is briefly reviewed and placed in perspective with other studies.

OPERATING ENERGY FOR POLLUTION CONTROL

Estimates of nationwide energy requirements for pollution control, as compiled from the literature, are presented for electric powerplants, industry, municipal wastewater teratment plants, and municipal solid waste disposal. All energy values have been converted to primary thermal energy equivalents using the following conversion factors:

Electricity. . .	10,666 Btu primary/kWh electrical, corresponding to a conversion efficiency of 32%
Oil.	6×10^6 Btu primary/barrel oil, corresponding to residual fuel oil
Coal	24×10^6 Btu primary/ton coal

Comparison of energy estimates from different literature sources is complicated by the following factors:

- The estimates are for different years.
- Compliance with different sets of regulations is assumed in different studies.
- Some estimates are for total energy required for control, and others are for incremental energy required for compliance with specific regulations.

- Energy accounting is incomplete in most studies; that is, not all types of energy are taken into consideration (for example, electricity, fuels, energy for production of treatment chemicals, energy for maintenance of equipment, etc.).

- Methods of calculation range from gross, cursory estimates to detailed computer simulations. The assumptions involved are often numerous, and the manner in which they affect the results is difficult to determine unless a sensitivity analysis is performed in the study.

- In some cases, insufficient information is given to permit proper interpretation of the results.

For these reasons, an attempt has been made to outline the methods and assumptions used to arrive at each result. These descriptions are intended to facilitate interpretation of the results and are necessarily incomplete in some cases. The original references should be consulted for complete details.

Electric Powerplants

Thermal Pollution Control--

Closed-cycle cooling systems for controlling thermal pollution require energy beyond that required for once-through cooling systems. In a closed system, the cooling water from the condenser is passed through a cooling device (such as a cooling tower) in which heat is transferred to the atmosphere, and is then returned to the condenser. Additional energy is required to operate pumps and blowers in forced-draft cooling towers and to compensate for the loss in thermal efficiency of the powerplant. The loss in thermal efficiency is due to an increase in condenser temperature, which results in an increased turbine backpressure.

Estimates of energy requirements for thermal pollution control are presented in Table 2. For comparison, the estimated total U.S. energy requirement is also given for each year (1). The individual estimates are discussed in the following sections.

DSI (Development Sciences, Inc.)(2)--The calculation can be described by the following general equation:

$$\begin{pmatrix}\text{Energy}\\ \text{required}\end{pmatrix} = \begin{pmatrix}\text{Capacity}\\ \text{controlled}\end{pmatrix}\begin{pmatrix}\text{Energy required per}\\ \text{unit of capacity}\end{pmatrix} \qquad (1)$$

The capacity requiring control to meet Federal regulations is obtained from U.S. Environmental Protection Agency (EPA) estimates (11, 12) and is given as a function of plant type (fossil fuel or nuclear) and size. Implicit in these estimates are assumptions concerning the number of plants that will install closed-cycle cooling systems for reasons other than pollution

TABLE 2. OPERATING ENERGY REQUIREMENTS FOR THERMAL POLLUTION CONTROL AT ELECTRIC POWERPLANTS

Source	Reference number	Year	Primary energy required, 10^{15} Btu/yr: Thermal pollution control	Primary energy required, 10^{15} Btu/yr: Total U.S. consumption[a]
DSI	2[b]	1977	0.086	78
DSI	2[b]	1983	0.20	95
ERT	3	1983	0.22[c]	95
Michigan	4[b]	1983	0.17	95
Michigan	4[b]	1985	0.2	101
RPA	5	1980	0.27	86
Cywin	6	1980	0.13	86
Temple, Barker & Sloane	7	1980	0.0[d]	86
Temple, Barker & Sloane	7	1985	0.2	101
Hirst	8	1970	0.16	-
Economics of Clean Water	9	1977	0.43	78
Economics of Clean Water	9	1983	0.79	95
NCWQ	10[b]	1983	0.045 to 0.29	95

[a] U.S. Government estimates (1). [b] Draft report subject to revision.

[c] Includes fossil-fueled steam electric plants only. If nuclear plants are assumed to make approximately the same contribution, the total energy requirement is roughly 0.4×10^{15} Btu.

[d] Indicates value is less than 0.1.

control regulations, and the number of plants that will receive exemptions under Section 316(a) of the Federal Water Pollution Control Act of 1972. Section 316(a) permits either the Federal or State environmental protection agencies to grant exemptions to effluent limitations for thermal discharges when it can be demonstrated "to the satisfaction of the Administrator" that the effluent limitations are more stringent than necessary for the protection of fish and other wildlife in the receiving body of water.

The energy required per unit of capacity is also given as a function of plant type and size. The values range from 1.7% to 3.2% of plant capacity for fossil-fueled plants, and from 2.3% to 4.2% for nuclear plants. The source of these figures is not discussed except to say that they are based on an analysis of forced-draft cooling towers. No distinction is made between new and retrofit systems.

ERT (Environmental Research and Technology, Inc.)(3)--Murphy, Mahoney, et al., of Environmental Research and Technology also use Equation 1. An energy penalty for thermal pollution control is assumed--2% for new plants and 3% for existing plants. These values are averages of data for forced-draft cooling towers culled from the literature. The capacity requiring control is calculated based on data from Reference 11. The incremental energy required for pollution control is calculated for each of three time periods: the baseline year, 1974; the period 1975 to 1978; and the period 1979 to 1984. An industry growth rate of 4.16%/yr is assumed in the calculations for the latter two periods. An additional assumption is made that 65% of the plants that employed closed-cycle cooling in 1974 did so for nonenvironmental reasons. The energy requirement of 0.22 quad for 1983 is obtained by adding together the values for the three time periods listed.

The result obtained in the ERT study applies to only fossil-fueled steam powerplants. It was found in the DSI study (2) that the energy required for thermal pollution control at nuclear powerplants is approximately the same as that required at fossil-fueled plants. If this result is combined with the ERT result, a value of approximately 0.4 quad is obtained for thermal pollution control at all powerplants in 1983. This value is a factor of 2 greater than the one obtained by DSI, despite the fact that the two studies used essentially the same methodology and the same data sources. One factor that tends to make the ERT value higher is the use of an average energy penalty. For example, applying the values of 2% for new units and 3% for retrofit units to the DSI capacity data increases the DSI energy estimates by 29% for 1977 and 26% for 1983. The remaining discrepancy between the two studies reflects the large effect exercised by the uncertainties concerning Section 316 exemptions under the Federal Water Pollution Control Act of 1972.

Michigan (University of Michigan study performed by Davidson, Ross, et al.)(4)--The value for 1983 is quoted from Reference 11. A 15% increase in energy consumption from 1983 to 1985 is assumed to obtain the value for 1985.

RPA (Resource Planning Associates)(5)--Bailly, Cushman, and Steinberg of Resource Planning Associates estimate the energy requirement to be 125,000 barrels/day (bpd) of oil. The source of the estimate is not discussed, but it presumably represents an interpolation between EPA's estimates (11) of 375,000 bpd before exemptions and 80,000 bpd after exemptions.

Cywin (6)--Equation 1 is used with an EPA estimate of 70,000 Mw requiring control in 1980 and an assumed fuel penalty of 3% for closed-cycle cooling.

Temple, Barker & Sloane (7)--No details of the calculations are available.

Hirst (8)--Equation 1 is used, with 50% of the 1970 generating capacity (arbitrarily) assumed to be controlled, and an average energy penalty of 2% assumed for closed-cycle cooling.

Economics of Clean Water (9)--No details of the calculations are given.

NCWQ (National Commission on Water Quality (10)--A simulation model is used to calculate the energy requirement for 21 alternative scenarios. Included are alternative assumptions concerning the number of plants receiving exemptions, the number of plants affected by State regulations, alternative age and size criteria for subcategorizing the industry, and alternative financial assumptions. An average annual growth rate of 6% is assumed for industry capacity and 2.2% for sales. Two of the scenarios are employed to establish upper and lower bounds on the energy required. In the lower-bound scenario, the number of Section 316 exemptions is assumed to be high (about 80% of affected capacity), and no additional units are assumed to be affected by State-level standards. In the upper-bound scenario, about 40% of capacity is assumed to receive exemptions, and State standards are assumed to require closed-cycle cooling at all unexempted plants of greater than 25 Mw capacity. No further details of the calculations are presented.

The values listed in Table 2 for 1983 agree to within a factor of about 4, excluding the lower NCWQ estimate. Extrapolation of the RPA and Cywin values from 1980 to 1983 would bring them within the range of the other values. Excluding the Economics of Clean Water estimate, the agreement is within a factor of approximately 2.5. This amount of variation in the results is quite reasonable considering the effect that the granting of variances can have on the actual energy required. For example, EPA estimates for energy required before and after exemptions differ by a factor of 4.7 for 1980 and a factor of 2 for 1977. The high and low estimates obtained by NCWQ differ by a factor of 6.4, largely because of different assumptions concerning the granting of exemptions.

Air Pollution Control--

Energy requirements for air pollution control at electric powerplants are associated primarily with the control of SO_x and particulate matter. Present standards for NO_x can be achieved by combustion modification techniques, such as low excess air firing and staged combustion, which incur little or no energy penalty and may in fact increase boiler efficiency by up to 2% (13-15) Hence energy requirements for NO_x control can be considered negligible at present. This situation could change in the future if, as anticipated by LaChapelle, et al. (14), stricter NO_x standards for stationary sources are adopted because of growth in stationary sources, delays in achieving automotive standards, and the need to improve ambient air quality. If separate NO_x flue gas treatment systems are eventually required, it is possible that the energy requirement for NO_x control could become comparable to that for SO_x control (15).

Estimates obtained from the literature on the energy requirements for air pollution control at electric powerplants are presented in in Table 3. The methodology employed in each of the studies is discussed briefly in the following sections.

TABLE 3. OPERATING ENERGY REQUIREMENTS FOR AIR POLLUTION CONTROL AT ELECTRIC POWERPLANTS

Source	Reference number	Year	Primary energy required, 10^{15} Btu/yr				
			SO_x scrubbers	Fuel oil desulfurization	ESP's	Total	Total U.S. consumption[a]
DSI	2[b]	1977	0.065	0.118	0.009	0.19	78
DSI	2[b]	1983	0.211	0.104	0.008	0.32	95
ERT	3	1983	0.77[c]	–[d]	0.064	0.83	95
Michigan	4	1985	0.51	0.15	0.01	0.80[e]	101
RPA	5	1980	0.21	–	–	0.21	86
MacDonald	16	1975	0.32	–	–	0.32	75
Cywin	6	1980	–	–	–	0.32	86
Temple, Barker & Sloane	7	1980	0.2	–	0.0[f]	0.2	86
Temple, Barker & Sloane	7	1985	0.3	–	0.0[f]	0.3	101
Hirst	8	1970	–	–	–	0.84[g]	–
Bendixen & Huffman	17	1974	0.062	–	–	–	73

[a] U.S. Government estimates (1). [b] Draft report subject to revision.

[c] Total for SO_x scrubbing and fuel oil desulfurization. [d] Dashes indicate data not presented in source.

[e] Includes 0.13×10^{15} Btu/yr for transportation of low-sulfur western coal.

[f] Indicates value is less than 0.1. [g] Total for powerplants and industry.

DSI (2)--Energy requirements are calculated by Equation 1. The capacity requiring scrubbers for SO_x control is an unpublished EPA estimate based on full compliance with Federal regulations (excluding State Implementation Plans) furnished by the Office of Planning and Evaluation. An energy penalty of 3.6% of plant capacity is used for limestone scrubbing, which includes energy for producing limestone and for sludge disposal. It is assumed that all oil- and coal-burning plants that do not require scrubbers will install electrostatic precipitators for control of particulate matter. An energy penalty of 0.194% of capacity is used for precipitators. All fuel oil burned by utilities is assumed to be desulfurized in the United States if its sulfur content exceeds 0.5%. The energy penalty used for desulfurization ranges from 1.2% to 8.6% of the energy content of the oil, depending on the sulfur content of the oil. These values are given without derivation. The amount of residual oil used by powerplants, together with its sulfur content, is obtained from U.S. Bureau of Mines data. The energy required for desulfurization is computed as the product of the amount of oil used (converted to Btu's) times the appropriate energy penalty for the sulfur content of the oil. Three sulfur ranges are considered: 0.5% to 1.5%, 1.0% to 2.0%, and greater than 2.0%.

ERT (3)--The values listed in Table 3 correspond to compliance through use of low-sulfur fuel and scrubbers only (Scenario 1 in Reference 3), and compliance with primary and secondary air quality standards and New Source Performance Standards (air quality goal 3a in Reference 3). Equation 1 is used with energy penalties of 7.0% for SO_x scrubbers [taken from the Michigan study (4)]

0.2% for electrostatic precipitators, and 3% to 6% for fuel oil desulfurization [from the Michigan study (4)]. The capacity requiring control by each technique is based on extrapolation to 1983 of 1974 survey data on the distribution of generating capacity by size, region, and fuel type. An annual growth rate of 4.16% is assumed, and dispersion modeling is employed to determine compliance with ambient air quality standards.

The energy requirement for control of sulfur oxides can vary considerably depending on assumptions made for growth rate and regulations met. For example, assumption of a 6.73% annual growth rate increases the energy requirement from 0.77 quad to 1.07 quad (3). Compliance with State Implementation Plans and nondeterioration regulations (in addition to the above-mentioned regulations) increases the energy requirement from 0.77 quad to 1.05 quads (3). The higher growth rate and stricter regulations together result in an energy requirement of 1.4 quads (3). The higher growth rate and use of Best Available Control Technology (BACT) yield an energy requirement of 2.0 quads in 1983 (3).

On the other hand, conversion of existing oil- and gas-fired plants to coal firing (where possible) results in only a small increase (about 5% or less) in the energy required for control of sulfur oxides (3). The range of energy requirements obtained in the ERT study is considered further in Section 6. The values listed in Table 3 were selected as representing the most plausible set of assumptions. They correspond essentially to the "average" case for Scenario 1 in Table 26 (Section 6).

Michigan (4)--An energy penalty of 7.0% for SO_x scrubbers is assumed, based on data from installations on four large powerplants. A penalty of 0.12% is used for electrostatic precipitators, of which 0.02% is for capital equipment. A penalty for fuel oil desulfurization of 3.5% to 5.8% was calculated from available data on a single desulfurization process. A penalty of 3.4% is estimated for transport of low-sulfur western coal. The capacities controlled by each method in 1985 are calculated from the following assumptions:

- The total energy required to produce electricity is 30% of the national energy total of 115 x 10^{15} Btu.
- The ratio of low-sulfur coal to coal used in plants equipped with scrubbers is 1:1. The ratio of low-sulfur oil to desulfurized oil is 1:1.
- One-half of low-sulfur coal production is Western coal subject to the transportation energy penalty.

RPA (5)--The calculation is based on the following assumptions:

- 90,000 Mw controlled (from EPA sources) with a load factor of 65%.

- Energy penalty of 5% of plant output for SO_x scrubbing.

- Scrubber stream factor of 95%.

MacDonald (16)--A unique method is used based on the Federal Energy Office estimate of the 1975 fuel deficit (225 million tons of coal) that would have resulted from enforcement of existing State Implementation Plans (SIP's) with no switching to gas or oil. Assuming limestone scrubbers are used to control SO_x emissions, SIP's would thus require installation of scrubbers at powerplants consuming a total of 225 million tons/yr of coal. An energy penalty of 6% for scrubbing is assumed, which results in an energy requirement of 13.5 million tons of coal (6% of 225 million tons), or 0.32 quad. Calculations are also made assuming energy penalties of 4%, 5%, and 7% for scrubbing; the resulting energy requirements range from 0.21 quad to 0.37 quad.

The corresponding energy requirement for using low-sulfur western coal to make up the fuel deficit is also computed. Transportation of western coal to eastern powerplants is found to result in an energy penalty of 35 million barrels/yr of oil, or 0.21 quad.

Cywin (6)--No details of the calculations are given.

Temple, Barker & Sloane (7)--No details of the calculations are given.

Hirst (8)--Estimates are obtained from the literature on energy requirements for 90% particulate removal and 70% SO_x removal at powerplants, furnaces, cement plants, incinerators, and fossil-fuel cleaning facilities. The sum of these values is arbitrarily increased by 50% because of increasingly strict air quality standards and because several industrial air pollution sources were not considered (8).

Bendixen and Huffman (17)--It is assumed that total 1974 generating capacity (1.1×10^9 Mwh) is fed 3.5% sulfur fuel and controlled with limestone scrubbers. The resulting energy requirement of 62 trillion Btu represents an energy penalty of 0.53% of powerplant fuel input, which is an order of magnitude too low. This value is based on data from a conceptual design and cost analysis of the limestone wet scrubbing process published in 1969 (18). The power requirement obtained in that study is much lower than values reported later from large-scale field demonstration units (4, 19). In addition, the energy penalty for stack-gas reheat is not included in Bendixen and Huffman's calculation, since the need for reheat was considered debatable at that time.

From this discussion, it is apparent that the first three studies listed in Table 3 represent the most thorough analyses of the problem. The ERT and Michigan results are in close agreement on total energy, although the estimates for individual control methods display somewhat greater differences. Part of the discrepancy between these estimates and the DSI value for 1983 is due to the difference in unit energy consumption values used for scrubbers; that is, 3.6% in the DSI study, and 7.0% in the other two studies[a]. Applying a 7% energy penalty to the DSI data yields a total energy requirement of 0.25×10^{15} Btu in 1977 and 0.52×10^{15} in 1983. The three estimates for the mid-1980's are than in agreement to within 40%. Considering the number of assumptions required in the analyses and the uncertainties in the data employed, this degree of agreement is regarded as excellent.

Wastewater Treatment--
According to Reference 12, energy requirements for wastewater treatment at electric powerplants are negligible compared with those for air and thermal pollution control. To achieve no discharge of pollutants by treating all wastewater streams in a central facility, the energy penalty is estimated to be less than 0.01% of plant fuel input (12).

Industry

Much less relevant information is available for the industrial sector than for powerplants. Hence, generally less sophisticated methods have been used to estimate the energy rquirements for pollution control. The various estimates obtained from the literature survey are listed in Table 4. Each of these estimates is discussed briefly in the following sections.

DSI (2)--
The calculation is based on incremental (as a result of Federal regulations) capital investment in pollution control equipment estimated by the Council on Environmental Quality (CEQ). This schedule assumes an increasing baseline value; that is, it is assumed that an increasing amount of pollution control equipment would be installed over the time period involved, regardless of Federal legislation (as a result of State and local regulations, pressure from citizens groups, etc.). This baseline value is subtracted from the total cumulative investment to obtain the incremental investment resulting from Federal regulations. As a result, the investment schedule exhibits a maximum in 1978 (air)

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[a] The total energy penalty for scrubbing consists of preplant (mining, transportation, and preparation of limestone), inplant (scrubber operation and flue-gas reheat), and postplant (sludge disposal) energy usage. The inplant energy penalties used were 3.5% in the DSI study and 5% in the other two studies. Recent EPA publications (20, 21), which reflect experience gained with demonstration-scale scrubbing systems, use inplant energy penalties of 3.4% to 5%. Thus the range of values used in the studies listed in Table 3 is consistent with presently available data on energy requirements for flue-gas scrubbing.

TABLE 4. OPERATING ENERGY REQUIREMENTS FOR INDUSTRIAL POLLUTION CONTROL

Source	Reference number	Year	Primary energy required, 10^{15} Btu/yr			
			Air	Water	Total	Total U.S. consumption[a]
DSI	2[b]	1977	0.50	0.23	0.73	78
DSI	2[b]	1983	0.51	0.28	0.78	95
Michigan	4	1985	0.40	0.55	0.95	101
EEI	22	1977	–[c]	–	0.88	78
NCWQ	10[b]	1977	–	0.38	–	78
NCWQ	10[b]	1983	–	0.82	–	95
Cywin	6	1980	0.27	0.09	0.36	86
RPA	5	1980	–	0.09	–	86

[a] U.S. Government estimates (1). [b] Draft report subject to revision.

[c] Dashes indicate data not presented in source.

or 1980 (water) that is reflected in the resulting energy values. For water pollution control, the following relationship is used:

$$\begin{pmatrix}\text{Energy}\\ \text{required}\end{pmatrix} = \begin{pmatrix}\text{Cumulative incremental}\\ \text{investment in water}\\ \text{pollution control equipment}\end{pmatrix}\begin{pmatrix}\text{Energy consumed}\\ \text{per dollar invested}\end{pmatrix} \qquad (2)$$

The incremental investment schedule is broken down by two-digit SIC numbers as given by CEQ. All calculations are made with 1973 dollars. Energy consumption coefficients are derived from data on 81 industrial sectors, with three plant sizes included in each sector.

Energy required for production of chemicals used in treatment is estimated in an analogous manner and found to be negligible (0.6%) by comparison with the direct operating energy.

The calculation for air pollution control is based on CEQ's incremental investment schedule together with a breakdown of investment by control device, supplied to EPA by Batelle Columbus Laboratories (23). The relationship used is:

$$\begin{pmatrix}\text{Energy required}\\ \text{for device i}\end{pmatrix} = \begin{pmatrix}\text{Incremental capital}\\ \text{investment in device i}\end{pmatrix}\begin{pmatrix}\text{Energy consumption}\\ \text{coefficient for device i}\end{pmatrix} \qquad (3)$$

Energy consumption coefficients (i.e., energy consumed per dollar of capital cost) are given for each control device without derivation.

Michigan (4)--
The calculation of energy for water pollution control is similar

to the method used by DSI, except that CEQ-estimated operating and maintenance costs are used rather than capital costs. An average energy consumption coefficient of 0.2×10^6 Btu/dollar of operating and maintenance cost is derived from data on several selected industries. This value includes energy for capital construction and indirect operating energy for chemicals, as well as direct operating energy in the form of fuel and electricity.

Air pollution control is divided into combustion and noncombustion processes. For combustion processes, energy penalties of 7.0% for SO_x control and 0.12% for particulate control are assumed, as in the calculation for powerplants. In addition to the assumptions made in the latter calculation, the following assumptions are made for the industrial sector:

- The ratio of industrial consumption of coal and oil to electrical powerplant consumption is the same as it was in 1972.
- Industrial coal consumption is primarily low-sulfur coal.
- Of the industrial oil used, the ratio of low-sulfur oil to desulfurized oil is 1:1.

A very crude approximation is made for the energy requirement for noncombustion air pollution control. Only particulate control using electrostatic precipitators, cyclones, and baghouses is considered. The calculation is made using the following assumptions:

- Total particulate emissions of 13.3×10^6 tons/yr (1970 value).
- Average loading of 5 grains/standard cubic foot (scf).
- Average energy requirement of 1.3 hp/cubic foot per minute (cfm), based on Reference 24.

EEI (Edison Electric Institute)(22)--
The value listed in Table 4 represents projected electrical energy consumption for pollution control and is based on a 1972 survey of electric utilities made by Edison Electric Institute. The value of 0.88×10^{15} Btu was obtained from the total estimated consumption for the period 1973 to 1977, excluding the values for sewage treatment, waste disposal, and waste recycling given in Reference 22. This value of 16.56×10^9 kWh was converted to primary energy using the conversion factor 10,666 Btu/kWh to yield 0.177×10^{15} Btu. The final value was obtained by dividing by 0.20 to account for the fact that the survey covered only 20% of total electric utility sales to industry (personal communication with S. B. Baruch, Edison Electric Institute, New York, NY, April 23, 1976).

NCWQ (10)--
Total energy requirements for wastewater treatment to meet Federal regulations were determined by detailed studies of nine industrial categories:

- Canned and preserved fruits and vegetables
- Inorganic chemicals
- Iron and steel
- Metal finishing
- Organic chemicals
- Petroleum refining
- Plastics and synthetics
- Pulp and paper
- Textiles

Details of the individual studies are not given. The energy requirement for all other industries is calculated from the total of the above industries using the ratio of total operating and maintenance costs of the two groups. The energy required by industries in the "all other" category is 21% of the total for 1977 and 9% of the total for 1983. The energy values are incremental above the 1973 base year consumption and are based on 1973 production capacity.

Cywin (6)--
The value for air pollution control is given without explanation. The value for water pollution control is based on flow rates and the treatment level required for each of the industries for which effluent limitations have been promulgated. This represents some 50% of the pending permit applications for industrial point sources, but most of the major discharges are included (6).

RPA (5)--
The estimate is given, without explanation, as 40,000 barrels/day of oil.

The most credible estimates are those of DSI, Michigan, NCWQ, and EEI. The agreement between the DSI and EEI values for 1977 is remarkable in that they were obtained by entirely different methods. It should be noted, however, that the results of the two studies represent different quantities. The EEI value includes electrical energy only, and the DSI value includes fuels and energy for production of chemicals, although the latter makes a negligible contribution to the total. Furthermore, the DSI value represents incremental energy consumption resulting from Federal regulations. The EEI value represents anticipated actual consumption for pollution control, which is different than both the total energy required to meet all Federal regulations and the incremental energy required to meet Federal regulations.

Municipal Wastewater Treatment Plants

Results of the literature survey are summarized in Table 5. Each value is noted as being either incremental energy required for compliance with Federal regulations or total energy required for wastewater treatment. The studies are discussed in the following sections.

TABLE 5. OPERATING ENERGY REQUIREMENTS FOR MUNICIPAL WASTEWATER TREATMENT PLANTS

Source	Reference number	Year	Primary energy required, 10^{15} Btu	Comment	Total U.S. consumption,[a] 10^{15} Btu
DSI	2[b]	1977	0.036	Incremental	78
DSI	2[b]	1983	0.25	Incremental	95
Michigan	4	1981	0.26	Incremental	89
EEI	22	1971	0.053	Total, electrical energy only	-[c]
EEI	22	1977	0.19	Total, electrical energy only	78
RPA	5	1980	0.055	Incremental above 1968 baseline	86
RPA	5	1980	0.084	Total	86
Cywin	6	1974	0.04	Total	73
Cywin	6	1977	0.06	Total	78
Cywin	6	1980	0.10	Total	86
Bendixen & Huffman	17	1968	0.029	Total, from 1968 inventory of municipal plants	-
Bendixen & Huffman	17	1974	0.18	Total, tertiary treatment of all wastewater	73
Hirst	8	1970	0.29	Total, secondary treatment of all wastewater	-
NCWQ	10[b]	1973	0.15	Total, excluding chemicals production	-
NCWQ	10[b]	1990	0.35	Total, excluding chemicals production	-

[a] U.S. Government estimates (1). [b] Draft report subject to revision. [c] Dashes indicate data not presented in source.

DSI (2)--

The calculation is based on the incremental investment schedule estimated by CEQ and plant operating and capital cost data from Reference 25. A hypothetical mix of plant type and size is assumed and combined with capital cost data to determine the number of plants of each type and size that can be built according to the incremental investment schedule. Plant operating data are then used to determine direct and indirect (for chemicals and sludge disposal) operating energy as a function of plant type and size. Multiplying these energy values by the number of incremental plants in each category yields the total incremental energy requirement.

Michigan (4)--

The calculation uses the CEQ investment schedule together with an energy coefficient of 0.117×10^6 Btu/1963 dollar, which is devalued to 0.089×10^6 Btu/1972 dollar. The energy coefficient is obtained from energy input/output analysis (26, 27). The accuracy of this method is checked by making the calculation for 1971 and comparing the result with a more detailed analysis made with data available for that year. The latter estimate is based on unit operating data from Smith (28), unpublished EPA data, an original survey of 80 treatment plants in Michigan, and the 1968 inventory of municipal treatment plants (29). Agreement to within 40% is obtained.

EEI (22)--The survey data for 1971 and the estimated data for 1977 were divided by 0.20 to account for the 20% coverage of the survey previously noted. The values correspond to the data for SIC 49, "Sewage Treatment." Although SIC 49 also includes utilities, such data were excluded from the survey (22). As noted in Table 5, the survey data represent electrical energy only; fuel and energy to produce treatment chemicals are not included.

The value of 0.053 x 10^{15} Btu for 1971 agrees exactly with the detailed estimate of electrical energy for 1971 obtained in the Michigan study (4). Fuels and treatment chemicals account for 29% of the total energy requirement in the latter study. If this ratio is applied to the EEI data, the total operating energy is found to be 0.075 x 10^{15} Btu for 1971 and 0.27 x 10^{15} Btu for 1977.

RPA (5)--
The calculation assumes that the fuel penalty resulting from Federal regulations is equal to the incremental energy consumption above the 1968 level, which is taken from the 1968 inventory of municipal treatment plants (29). Adding the value of 0.029 x 10^{15} Btu for 1968 yields the total value for 1980. No additional details of the calculation are given.

Cywin (6)--
The estimates include electrical energy and fuels but exclude energy for production of chemicals. The 1968 inventory of municipal treatment plants serves as the basis for the estimates. The following assumptions are used to extrapolate the 1968 data:

- Secondary treatment will be required at all plants by 1980.
- No more than 10% of all sludge is incinerated. The balance is land-filled or used for fertilizer.
- Activated sludge treatment is utilized to attain secondary standards.
- Advanced waste treatment is required for about one-half of the plants (those on heavily polluted streams or lakes).

The 1974 estimate is obtained by adding all new projects to the 1968 inventory. For 1977, the 1974 value is increased by 11% to account for growth in sewered population, and the impact of secondary treatment requirements is added. The difference between the 1977 and 1980 values is almost entirely a result of energy required for advanced wastewater treatment.

In addition to energy associated with production of treatment chemicals, the analysis specifically excludes energy required for space heating of plant buildings and collection system pumping requirements. Energy recovery by collection of methane is also excluded from consideration.

Bendixen & Huffman (17)--
The 1974 value is obtained as the product of the 1974 U.S. population and the electrical energy requirement for tertiary treatment of 0.22 kWh/person-day quoted by Smith (28) from the 1968 inventory of municipal treatment plants. The latter value is based on tertiary treatment plants serving a total of 325,000 people. Fuel and energy for production of chemicals are not considered.

Hirst (6)--
The calculation employs data on electricity consumption by municipal treatment plants as a function of plant size. The total electrical energy consumption is obtained by means of the following arbitrary assumptions:

- The average plant size is 30,000 population equivalents (PE).
- The average PE/population ratio is 3.
- Total 1970 wastewater, municipal and industrial, is treated to the secondary level.

Fuel and energy for production of chemicals are not considered.

NCWQ (10)--
The result is based on the 1974 U.S. EPA Needs Survey (see Reference 10 for details) and represents the total net energy required for operation and maintenance, including wastewater collection but excluding energy for chemicals. The net energy requirement is that in excess of the energy that would be supplied by methane produced from sludge digestion. This is the only study that takes methane production into account. The estimate for 1980 is based on a projection of the population that would be served by municipal treatment plants in 1990.

The EEI and NCWQ results, which are based on more recent survey data, are significantly higher than the values given by RPA and Cywin, which are based on 1968 survey data. The 1977 estimate of Cywin is a factor of 4 smaller than the EEI value of 0.27 x 10^{15} Btu (corrected for fuel and chemical energy). The 1977 DSI estimate is even lower, but this is due to the fact that it is incremental energy only. If the 1973 NCWQ value is taken as the baseline for the DSI value, the total value for 1977 is 0.19 x 10^{15} Btu--in good agreement with the EEI value of 0.27 x 10^{15} Btu.

Municipal Solid Waste Disposal

Solid waste represents a considerable energy resource. It is estimated by Huffman (30) that the total fuel value of all the municipal, industrial, mineral, and agricultural waste produced in the United States in 1970 is 8.5 x 10^{15} Btu, or 12% of the total national energy consumption. Of this total, it is estimated that 1 x 10^{15} to 2 x 10^{15} Btu are economically recoverable

(30). It is estimated by Franklin, et al (31) that an additional 0.4 x 10^{15} Btu can be saved annually by recovering and recycling scrap metals in solid waste.

Because solid waste disposal is potentially an energy-producing operation, it should not strictly be included in the present context. However, if energy recovery is not practiced (typically the present situation in the United States), then energy is required for collection, transportation, landfilling, and incineration of solid waste. Hence, solid waste disposal is included in this report for completeness.

Estimates of energy requirements for collection, transportation, landfilling, and incineration of municipal solid waste are given in Table 6. The potential energy recovery from solid waste incineration and from recycling materials is also listed. Each of the estimates is discussed in the following sections.

TABLE 6. ENERGY REQUIREMENTS FOR MUNICIPAL SOLID WASTE DISPOSAL

			Primary energy required, 10^{15} Btu/yr[a]			
Source	Reference number	Year	Collection, transportation, and landfilling	Electricity for incineration	Electricity production from incineration	Recycling
Hirst	8	1970	0.075	0.027	(0.27)	(0.44)
RPA	5	1973	0.087	-[b]	-	Negligible
RPA	5	1980	Negligible[c]	-	(0.28)	(0.15)
Cywin	6	1980	-	-	(0.44)	(0.077)

[a] Values in parentheses represent energy credits.

[b] Dashes indicate data not presented in source.

[c] Incremental energy requirement above the 1973 value because of Federal standards. It is assumed that improved collection practices will offset any additional energy demand because of stricter standards for municipal waste management.

Hirst (8)--
The energy requirement for collection, transportation, and landfilling is based on an average value of 300,000 Btu/ton obtained from data on three cities: Oak Ridge, TN; Los Angeles, CA; and New York, NY. This value is multiplied by the estimated 250 million tons of solid waste generated in the United States in 1969 to yield the value of 0.075 quad listed in the table.

The electricity requirement for solid waste incineration is based on an average requirement of 10 kWh/ton and the assumption that all 250 million tons of municipal waste generated in 1969 were incinerated.

For the calculation of electricity production from solid waste incineration, it is assumed that energy is recovered from 10% of the solid waste generated in 1969 at a rate of 1,000 kWh/ton.

The energy savings from recycling materials is based on energy data for existing production methods and production from recycled materials. The data cover three materials: steel, aluminum, and paper. The value of 0.44 quad in the table is obtained by assuming that one-third of the 1970 U.S. production of these materials is manufactured from recycled material.

RPA (5)--
The value for collection, transportation, and landfilling is obtained as the sum of the 1968 baseline value (0.074 quad) and an incremental value of 0.013 quad resulting from Federal standards.

The 1980 estimate of 0.15 quad for recycling materials is based on an EPA estimate of approximately 0.075 quad for recycling aluminum, ferrous metals, and glass. RPA assumes an equal savings (0.075 quad) for recycling paper to obtain the total of 0.15 quad. A similar "calculation" is employed to obtain the value for energy recovered from solid waste incineration in 1980.

Estimates of energy savings resulting from changes in packaging practices are also given. Reduction of per capita consumption of packaging from the 1972 level to the 1958 level would result in an estimated savings of 0.58 quad/yr. Exclusive use of refillable bottles for beverages would save an estimated 0.25 quad/yr. These values are based on unpublished EPA estimates; they include energy saved because of the manufacture of smaller amounts of packaging materials as well as energy saved by reduction of solid waste loads.

Cywin (6)--
The values are given without explanation.

CAPITALIZATION ENERGY REQUIREMENTS

A complete accounting of the energy required for pollution control must include the energy expended in the fabrication and installation of pollution control equipment. A nationwide estimate of the capitalization energy required to meet Federal regulations, taken from the DSI study (2), is given in Table 7. The values in the table represent averages for the 11-yr period 1972 to 1982. The calculation utilizes an energy coefficient of 50,000 Btu/dollar of capital investment in pollution control equipment obtained from energy input-output analysis (26, 27). This coefficient is combined with the CEQ incremental investment schedule for pollution control equipment to obtain the results. Equipment replacement is not accounted for in the calculation.

Although no statement concerning accuracy is given in Reference 2, the values listed in Table 7 should probably be interpreted as order-of-magnitude estimates. As an indication of the reliability of the results, the Michigan study (4) reported values of capitalization energy for municipal treatment plants of

TABLE 7. CAPITALIZATION ENERGY REQUIREMENTS FOR POLLUTION CONTROL[a]

Sector controlled	Primary energy required, 10^{15} Btu/yr[b]
Powerplants:	
Thermal	0.01
Air	0.04
Industry:	
Air	0.05
Water	0.05
Municipal treatment plants	0.07
Total	0.22

[a] Data from Reference 2; draft report subject to revision.

[b] Average for the 11-yr period 1972 to 1982.

0.16 x 10^{15} Btu in 1971 and 0.29 x 10^{15} Btu in 1981. These estimates were obtained using the same methodology as in the DSI study.

UNIT ENERGY REQUIREMENTS OF POLLUTION CONTROL STRATEGIES

National energy estimates for pollution control are important for making policy decisions and in determining the areas where significant energy savings may be possible. But from the standpoint of energy conservation through the use of less energy-intensive control systems, the energy requirements of individual pollution control methods are of fundamental importance. Unit energy consumption data obtained from the literature survey are summarized in this section.

The ERT report (3) contains a large amount of information on energy requirements for pollution control methods related to powerplants. Many of these data should be applicable to combustion processes in general. Table 8 presents unit energy requirements in terms of preplant, inplant, postplant, and capital-related consumption. The energy requirements are given as percentages of plant fuel input and represent averages of data obtained from the literature.

The inplant energy penalty of 3% to 5.5% for flue-gas desulfurization is in agreement with the range of recent EPA estimates (20, 21) (which is 3.4% to 5%, as previously noted). However, data from various sources span a considerably wider range (Table 9).

TABLE 8. UNIT ENERGY REQUIREMENTS FOR POWERPLANT POLLUTION CONTROL[a]

Area	Energy requirement, percent of plant fuel input
Preplant:	
Limestone mining	0.06
Transport:	
Western coal	4.0
Control chemicals	0.2
Pretreatment:	
Oil desulfurization	3 to 6
Coal cleaning, physical	4 to 10
Coal cleaning, chemical	35 to 40
Coal liquefaction and gasification	15 to 40
Coal blending	0.5 to 2.0
Lime calcining and preparation	1.98
Inplant:	
Sulfur dioxide control: Flue-gas desulfurization	3.0 to 5.5
Particulate control:	
Multiple cyclones	~0.0
Electrostatic precipitators	0.1 to 0.3
Nitrogen oxides control: Combustion modifications	0 to 0.6
Thermal pollution control:	
Cooling ponds	1.0
Spray ponds	1.3
Mechanical draft towers	1.0 to 4.0
Natural draft towers	2.0 to 4.5
Wastewater control: Chemical treatment	<0.04 to 0.2
Unit conversions:	
Substitution of western coal	0.5
Coal conversion	-[b]
Supplemental fuel, solid waste	0.0
Fluidized bed combustion	5
Noise control	0.1
Intermittent control strategies:	
Fuel switching	Small.
Load shifting	Small.
Tall stacks	0
Postplant:	
Coal ash disposal	0.0 to 1.1
Sludge disposal	0.77 to 1.26
Capital energy requirements (included in preplant):	
Sulfur oxide control:	
Transport of western coal trains or pipelines	-[b]
Limestone scrubbing systems	0.2 to 0.5
Oil desulfurization facility	0.15
Particulate control: Electristatic precipitator	0.02[c]
Nitrogen oxide control: Combustion modifications	Negligible.
Thermal pollution control: Closed-cycle cooling system	Negligible.
Coal gasification or liquefaction plant	-[b]
Coal preparation facility	-[b]

[a] Data from Reference 3.

[b] A value was not determined, but the process cannot be assumed to be unimportant.

[c] This value is incorrectly listed as 0.2 in Reference 3.

TABLE 9. ENERGY REQUIREMENTS FOR NONREGENERABLE FLUE-GAS DESULFURIZATION SYSTEMS[a]

System	Plant	Energy requirement, percent of plant fuel input		
		Reheat	Process	Total
Limestone	Will County	1.5	4.0	5.5
Limestone	Unidentified	1.6	2.3	3.9
Limestone	Unidentified	3.9	4.7	8.6
Limestone	Will County	2.5	4.0	6.5
Limestone	Detroit Edison	5.4	4.1	9.5
Limestone	Widows Creek	3.2	1.7	4.9
Limestone	New unit	-[b]	-	3.4
Limestone	Existing unit	-	-	3.9
Nonregenerable	Unidentified	-	-	1.5 to 4
Lime	Unidentified	1.5	3.5	5.0
Lime	Unidentified	1.6	1.9	3.5
Lime	New unit	-	-	3.3
Lime	Existing unit	-	-	4.0
Molten carbonate	Unidentified	-	<1	-
Nonregenerable	Unidentified	-	-	3 to 6

[a] Data from Reference 3.

[b] Dashes indicate reference listed only total percentages.

A detailed breakdown of the energy required for both lime and limestone scrubbing [as compiled in the ERT study (3)] is presented in Table 10. In addition to the somewhat high values for inplant energy noted above, the values for preparation of fixating agent appear to be high. The value for lime scrubbing is about one-third of the energy required for preparation of the control chemical. It has been suggested that 10% of the energy for control chemical preparation is a more appropriate value for preparation of fixating agent (personal communication from E. L. Plyler, U.S. Environmental Protection Agency, Research Triangle Park, NC, January 14, 1977).

Regenerable scrubbing processes are an alternative to the throwaway or nonregenerable processes. The inplant energy requirements of a number of different regenerable and throwaway processes are compared in Table 11. This table is based on data given by Rochelle (19) and a recent study performed by Radian Corp. for the Electric Power Research Institute (32). Regenerable processes require additional inplant energy for operation of sulfur recovery units. On the other hand, nonregenerable processes require more preplant and postplant energy for production

TABLE 10. ENERGY REQUIREMENTS FOR LIME AND LIMESTONE FLUE-GAS DESULFURIZATION SYSTEMS[a]

Component	Energy requirement, percent of plant fuel input: Lime	Limestone
Preplant:		
Control chemical:		
Extraction	0.054	0.063
Preparation	1.98	0.0
Transport	0.085	0.195
Inplant:		
Reheat	1.5	1.5
Equipment	3.5	4.0
Postplant:		
Fixating agent:		
Extraction	0.017	0.029
Preparation	0.64	1.09
Transport	0.027	0.046
Fixated sludge: Transport	0.082	0.093
Total	7.9	7.0

[a] Data from Reference 3.

TABLE 11. OPERATING ENERGY REQUIREMENTS FOR FLUE-GAS DESULFURIZATION PROCESSES

Process	From Reference 19: Power	Fuel	Total inplant	From Reference 32: Power	Fuel	Total inplant
Throwaway scrubbing:						
Limestone scrubbing	2.2	1.6	3.8	2.2	1.5	3.7
Lime scrubbing	1.9	1.6	3.5	2.2	1.4	3.6
Double alkali	2.2	1.6	3.8	-	-	-
Chigoda (dilute sulfuric acid)	2.2	1.6	3.8	-	-	-
Regenerable scrubbing (to sulfur):						
Wellman-Lord (sodium sulfite)	4.5	3.1	7.6	2.4	5.5	7.9
Magnesium oxide	2.2	5.6	7.8	1.8	7.9	9.7
Ammonia-ammonium bisulfate	1.9	5.1	7.0	5.4	4.3	9.7
Citrate	2.0	3.1	5.1	1.6	4.7	6.3
Stone & Webster/Ionics (sodium hydroxide)	7.6	3.1	10.7	7.0	3.9	10.9
Catalytic/IFP (ammonia)	-	-	-	1.8	6.3	8.1
Atomics International (aqueous carbonate)	-	-	-	2.0	4.3	6.3
Sulfoxel	2.0	3.1	5.1	-	-	-
Dry processes:						
Catalytic oxidation	2.0	3.2	5.2	2.6	0.1	2.7
Copper adsorbtion	2.0	5.5	7.5	1.2	12.1	13.3
Westvaco (activated carbon)	-	-	-	2.6	6.3	8.9
Bergbau-Forschung/Foster Wheeler (char)	-	-	-	1.6	6.8	8.4

NOTE.—Dashes indicate data not presented in source.

of chemicals and sludge disposal. In addition, the regenerable processes should receive an energy credit for the product produced (either sulfur or sulfuric acid), provided there is a market for it. Otherwise, energy is required for disposal. It appears that several of the regenerable and dry processes (citrate, aqueous carbonate, sulfoxel, and catalytic oxidation) may be competitive with the throwaway processes in terms of total energy requirements.

Unit energy requirements for powerplant thermal pollution control using mechanical forced-draft cooling towers are given in Table 12 as a function of plant type and plant size. These values were obtained from the DSI study (2).

TABLE 12. ENERGY REQUIREMENTS FOR MECHANICAL, FORCED-DRAFT COOLING TOWERS FOR POWERPLANT THERMAL POLLUTION CONTROL[a]

Plant size, MW	Energy requirement, percent of plant output: Fossil-fueled plants	Energy requirement, percent of plant output: Nuclear plants
50	3.2	4.2
150	3.1	4.1
500	2.5	3.3
900	2.3	3.0
1,500	2.0	2.6
3,000	1.7	2.3

[a] Data from Reference 2; draft report subject to revision.

Energy requirements of gas absorption equipment for general scrubbing applications have been published by Teller (24) and are reproduced in Figure 1. These data are based on 90°F scrubbing liquid and emission levels not less than 1 part per million (ppm). Data on energy requirements for particulate control devices have been assembled by Teller (24) and by Stukel and Rigo (33). Their data are reproduced in Figures 2 and 3.

Stukel and Rigo also calculated the theoretical minimum (reversible) energy required to separate particulate matter and SO_2 from stack gases. They defined the thermodynamic effectiveness of the control process to be the ratio of the reversible work required to the actual work required; that is,

$$\text{Effectiveness} = \frac{W_{\text{reversible}}}{W_{\text{actual}}} \tag{4}$$

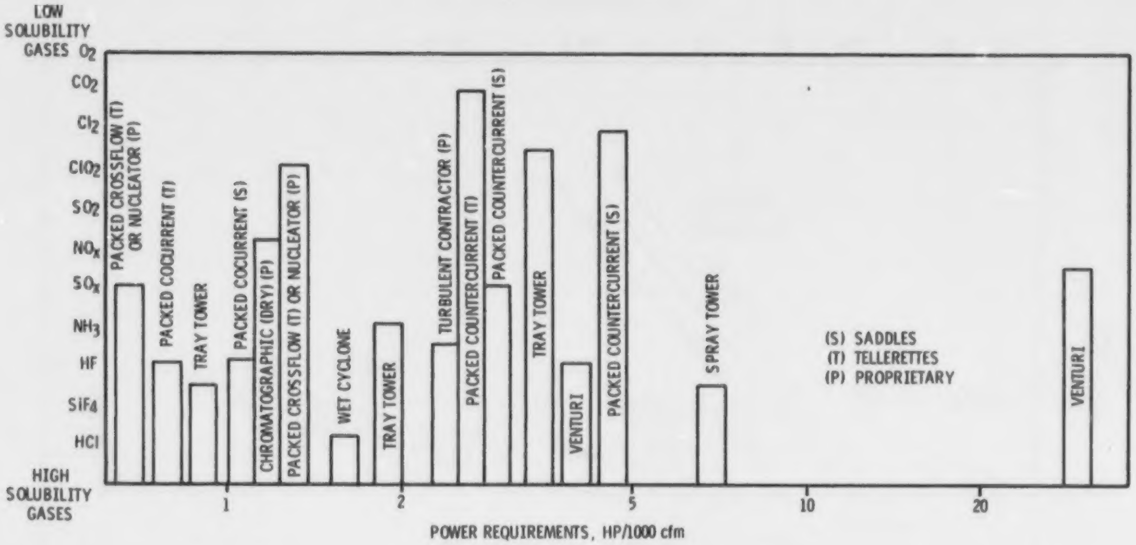

Figure 1. Energy requirements for gas absorption equipment (24).

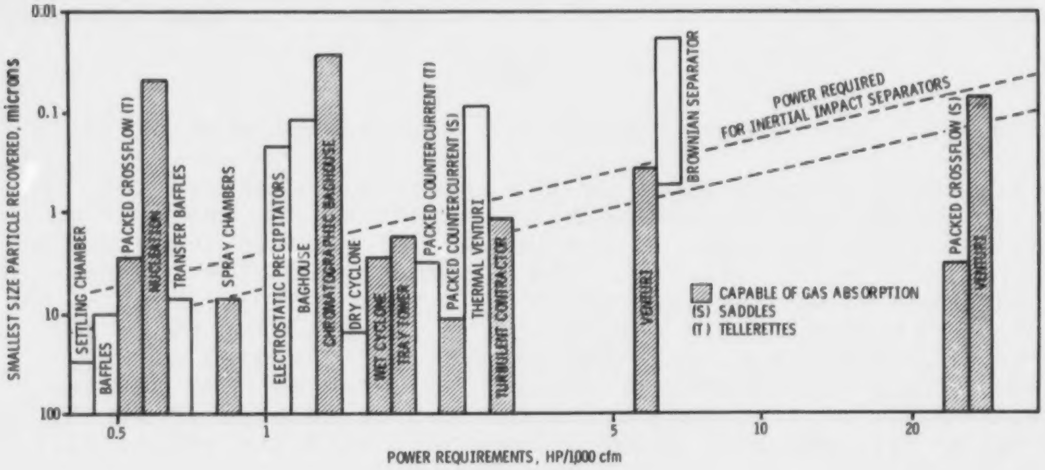

Figure 2. Energy requirements for particulate control devices (24).

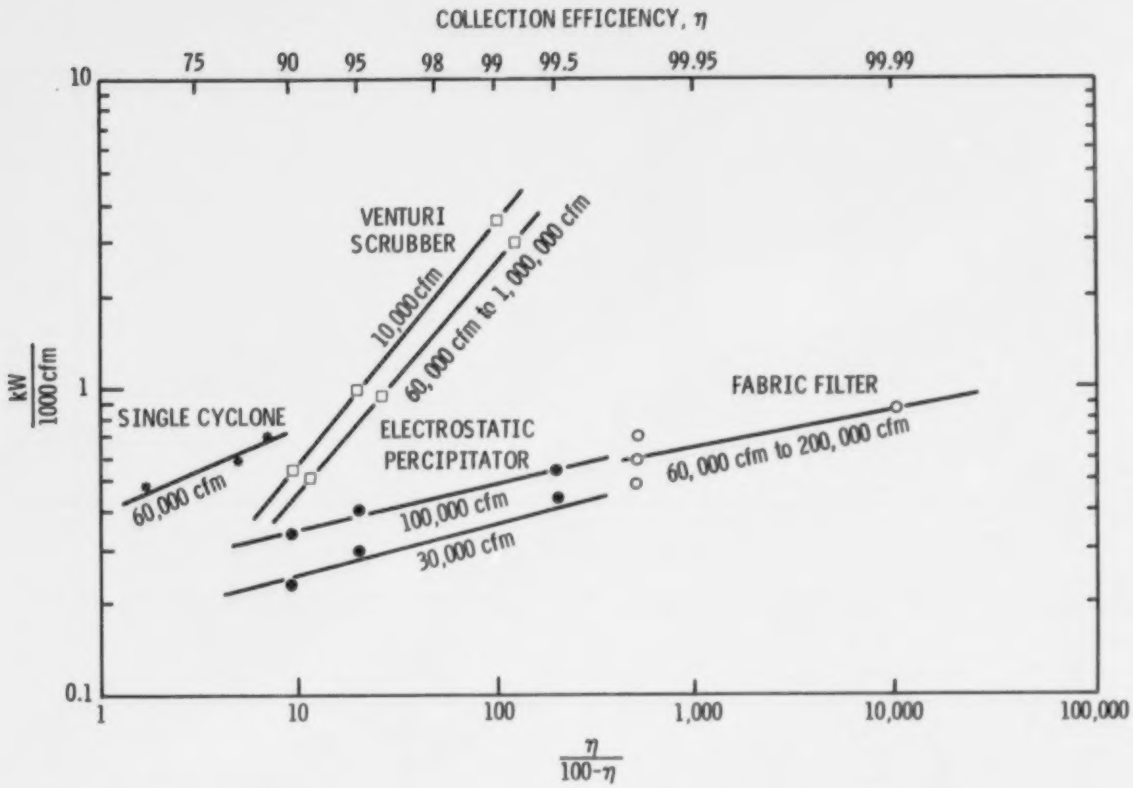

Figure 3. Energy requirements for particulate control (33).

The principal contributions to the reversible work are the kinetic energy of the species being separated and the work of unmixing, which is equal to the product of process temperature and the entropy of unmixing. The thermodynamic effectiveness of all flue-gas treatment techniques is extremely low, as shown in Figure 4 for particulate matter and in Table 13 for SO_2. The latter values correspond to SO_2 removal efficiencies of 90% (lower value) to 95% (higher value). A value of 2.9% for the effectiveness of limestone scrubbers was calculated in the Michigan study (4), which is in good agreement with the values listed in Table 13.

A large number of data, obtained by Smith (38) on electrical energy consumption by municipal wastewater treatment plants, are summarized in Figure 5. The data show that the electrical energy required for primary treatment is 0.2 to 0.4 kWh/1,000 gal. For secondary treatment, the requirement is 0.4 to 0.7 kWh/1,000 gal for trickling filter plants, and 0.9 to 1.1 kWh/1,000 gal for activated sludge plants.

Similar data for a number of tertiary treatment trains, also from Smith (28), are given in Table 14 and Figure 6. The energy

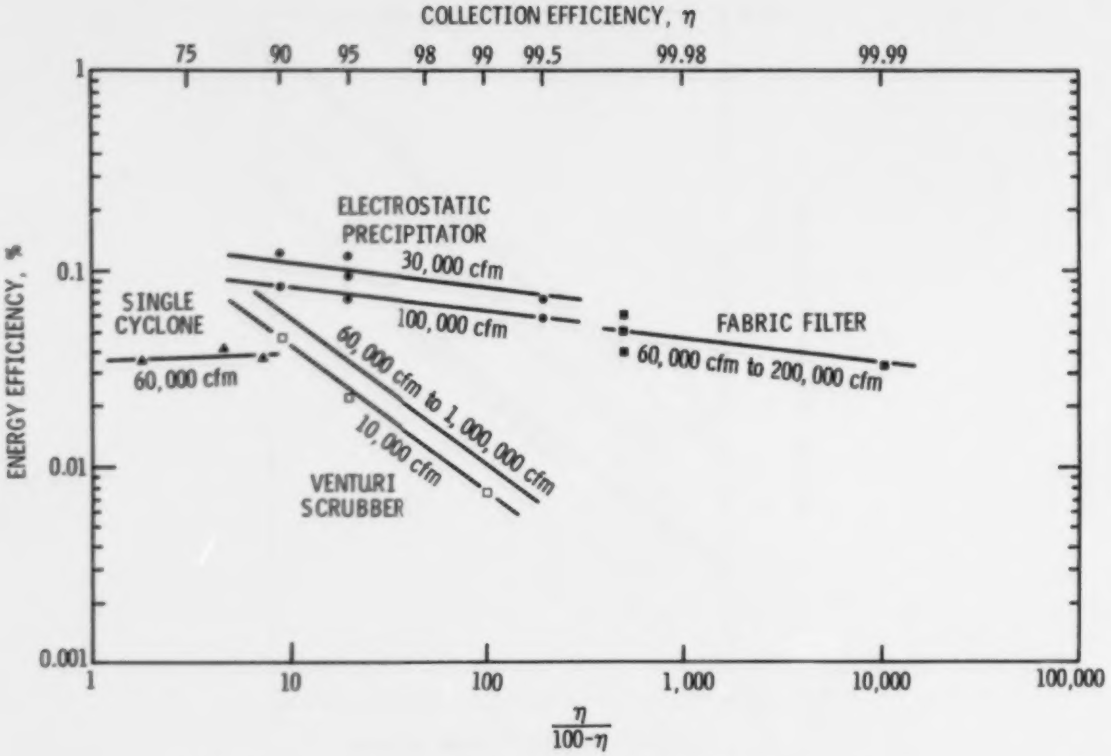

Figure 4. Thermodynamic effectiveness of particulate control devices (33).

TABLE 13. THERMODYNAMIC EFFECTIVENESS OF SO_2 CONTROL TECHNIQUES[a]

Control method	Effectiveness, %
Throwaway processes:	
Limestone scrubbing	2.2 to 2.4
Lime scrubbing	2.4 to 2.6
Sulfuric acid scrubbing	2.2 to 2.4
Regenerable processes:	
Sodium bisulfate/bisulfite	1.1 to 1.2
Magnesium oxide	1.1 to 1.2
Electrochemical sodium hydroxide regeneration	0.8 to 0.9
NH_3--bisulfate	1.7 to 1.8
Dry processes:	
Catalytic oxidation	1.6 to 1.8
Copper adsorption	1.1 to 1.2

[a] Data from Reference 33.

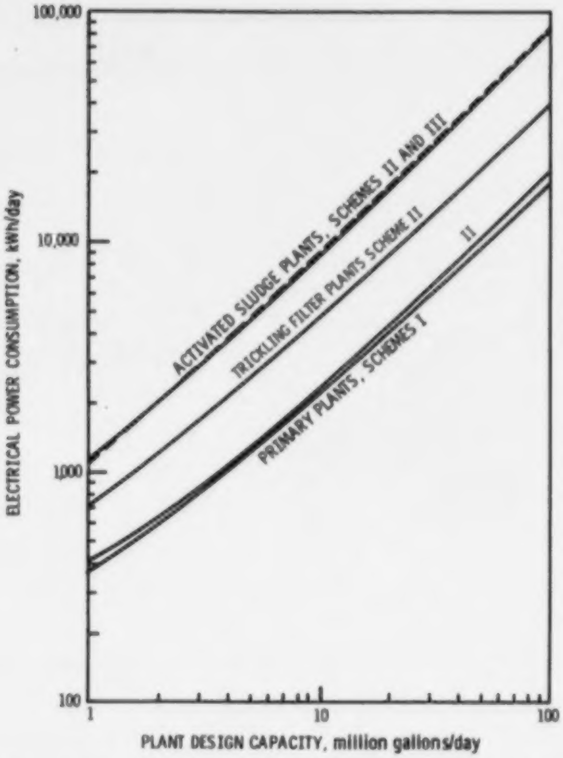

Figure 5. Electrical energy requirements for municipal wastewater treatment plants (28).

TABLE 14. ESTIMATED ELECTRICAL POWER CONSUMPTION FOR ALTERNATIVE TERTIARY TREATMENT TRAINS AFTER SECONDARY TREATMENT[a]

Advanced processes used	Treatment train							
	I	II	III	IV	V	VI	VII	VIII
Microscreening	115	-[b]	-	-	-	-	-	-
Alum addition and extra sludge handling	-	101	101	-	-	-	-	-
Lime clarification	-	-	-	52	52	52	-	52
Lime sludge dewatering	-	-	-	64	64	64	-	64
Lime recalcination	-	-	-	254	254	254	-	254
Recarbonation	-	-	-	-	-	-	-	94
Ammonia stripping	-	-	-	-	-	-	-	437
Nitrification	-	638	638	-	-	-	-	-
Denitrification	-	10	10	-	-	-	-	-
Multimedia filtration	-	-	100	100	100	100	100	100
Granular carbon adsorption	-	-	-	-	371	371	-	371
Carbon regeneration	-	-	-	-	20	20	-	20
Electrodialysis	-	-	-	-	-	1,341	-	-
Reverse osmosis	-	-	-	-	-	-	5,903	-
Total power consumption, kWh/day	115	749	849	470	861	2,202	6,003	1,302

[a] Data from Reference 28.

[b] Dashes indicate that the treatment train does not include the given processes.

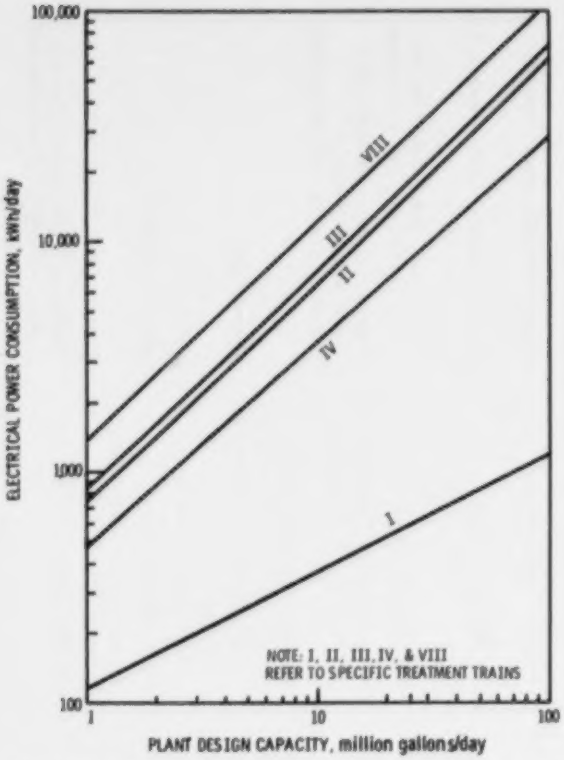

Figure 6. Electrical energy requirements for tertiary wastewater treatment trains (28). NOTE.—I, II, III, IV, and VIII refer to specific treatment trains defined in Table 13.

required is highly dependent on the particular train of processes employed. The electrical energy requirements range from about 0.11 kWh/1,000 gal for Train I (microscreening) to 6 kWh/1,000 gal for Train VII (multimedia filtration and reverse osmosis). These values are in addition to the energy required for primary and secondary treatment. Additional data taken from the NCWQ study (10) on advanced treatment techniques are summarized in Table 15.

TABLE 15. ENERGY REQUIREMENTS FOR ADVANCED WASTEWATER TREATMENT TECHNIQUES[a]

Technology	Technology capability	Energy and other requirements	State of development
Membrane technologies:			
Reverse osmosis	Removes dissolved materials of all sorts.	~8 kWh/1,000 gal.	Demonstration, semi-commercial.
Ultrafiltration	Removes large dissolved molecules, colloidal and suspended solids.	~8 kWh/1,000 gal.	Demonstration, semi-commercial.
Electrodialysis (including other electromembrane processes)	Removes only dissolved ionic species.	~10 kWh/1,000 gal.	Commercial for potable water, demonstration for wastewater.
Adsorption (mainly ion exchange)	Removes dissolved salts and other dissolved compounds.	Approximately one-third of the cost is chemicals.	Commercial for potable water and boiler feed; demonstration for wastewater.
Evaporation (including vapor compression)	Removes nonvolatile contaminants.	400 to 1,700 Btu/gal[b]. 62 to 87 kWh/1,000 gal (for vapor compression).	Commercial.
High gradient magnetic separation	Removes suspended material, preferably magnetic material.	~0.7 kWh/1,000 gal (depends on size).	Laboratory.
Filter-coalescence	Removes oil.	~0.1 kWh/1,000 gal.	Demonstration.
Wet oxidation	Destroys COD, phenols, cyanides, etc.	Depends on COD removal, ~0.34 kWh/lb COD.	Commercial.
Ozonation	Destroys COD, disinfects.	~9 kWh/1,000 gal.	Commercial for potable water, demonstration for wastewater.
Land treatment	Removes biodegradable solids, BOD, and nutrients.	Large land areas. 0.5 to 0.8 kWh/1,000 gal[c].	Full scale, very site specific.

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[a] Data from Reference 10; draft report subject to revision.

[b] This amount of energy would, at 40% efficiency, be used to generate 47 to 200 kWh/1,000 gal.

[c] For spray irrigation; other methods have lower requirements.

SECTION 5

DISTRIBUTION OF ENERGY REQUIREMENTS FOR POLLUTION CONTROL

The various relationships that exist among the data presented in the previous section are obscured by the scatter in the estimated energy requirements and by the diversity of assumptions on which the estimates are based. Hence, a single set of relatively consistent data was extracted from the information given in Section 3. A combination of the DSI (2) data for 1977 and the EEI (22) data was selected as representing the best combination of consistency and accuracy. In the following sections, these data are used to determine the distribution of pollution control energy requirements among pollution control sectors and pollutants. The distribution within the industrial sector is then determined on the basis of 1) estimates of energy required for pollution contol and 2) pollutant emissions.

DISTRIBUTION AMONG SECTORS

Estimates of the energy required for pollution control in 1977 are listed by sector in Table 16. Each of the given values requires some explanation.

TABLE 16. ENERGY REQUIRED FOR 1977 POLLUTION CONTROL, BY SECTOR[a]

Sector	Energy required, 10^{15} Btu		Percent of total energy requirement for pollution control at stationary sources	Percent of total U.S. energy requirement in 1977
	Nominal value	Estimated error bounds		
Industry	-[b]	-	58	1.3
Air	0.65	-	-	-
Water	0.35	-	-	-
Total	1.0	0.5 to 2.0	-	-
Power plants	-	-	20	0.4
Air	0.19	0.10 to 0.38	-	-
Thermal	0.15	0.07 to 0.29	-	-
Total	0.34	0.17 to 0.68	-	-
Municipal wastewater treatment	0.27	0.09 to 0.54	16	0.4
Municipal solid waste disposal	0.1	0.05 to 0.15	6	0.1
Total	1.7	0.8 to 3.4	100	2.2

[a] Part of the information contained in this table is based on draft reports, which are subject to revision.

[b] Dashes indicate that a value was not determined or does not apply.

The value of 1.0 quad for the industrial sector was obtained by rounding the EEI value of 0.88 quad. The value was rounded upward to take into account forms of energy other than electrical, since the EEI estimate includes only electrical energy. Few data are available on the fraction of industrial pollution control energy supplied by electricity. Data on water pollution control from six major industries given in Reference 10 yield values ranging from 80% to 100%, with the exception of petroleum refining. The value for the latter industry is 42% because of large fossil fuel use for sour water stripping. Values for air pollution control may be somewhat lower since about 30% of the energy required for flue-gas desulfurization may be nonelectrical energy used for flue-gas reheating. On the other hand, the ERT study (3) states that electrical energy accounts for 88% of the total energy consumption for flue-gas scrubbing. Using this value together with a breakdown of energy requirement by air pollutant type (see following subsection), a value of 81% was estimated for the fraction of industrial air pollution control energy supplied by electricity. Using this value for air pollution control and assuming an electrical fraction of 90% for water pollution control, an estimate of 84% for the fraction of total industrial pollution control energy supplied by electricity was obtained. This rather crude estimate agrees well with the value of 88% which results from rounding the EEI energy requirement to 1.0 quad.

The error bounds given for the industrial sector were obtained by assigning a factor of 2 accuracy to the EEI data. That these bounds are reasonable, and probably conservative, can be seen as follows. The EEI (22) survey data for 1971 yield a value of 0.41 quad, which should be a very conservative lower bound. Hence, the lower bound of 0.5 quad appears to be reasonable. According to the 1971 EEI data, 6.5% of all industrial electrical consumption is for pollution control. Assuming, as above, that approximately 90% of industrial pollution control energy is electrical, the total energy consumed for industrial pollution control is 7.2% of industrial electricity consumption. This value was increased to 10% to allow for increased pollution control activity from 1971 to 1977.

Electricity accounts for less than one-half the total energy consumed by industry (34). Therefore, industrial energy consumption for pollution control should be less than 5% (1/2 x 10%) of total industrial energy consumption. The fraction of total U.S. energy consumption used by the industrial sector is generally quoted as 30% to 40% (1, 35). Assuming a value of 78 quads for total U.S. consumption in 1977 yields a total industrial energy consumption of 23 to 30 quads. Taking 5% of this consumption yields an upper bound of 1.2 to 1.5 quads for industrial pollution control energy consumption. Thus the upper bound of 2.0 quads for the industrial pollution control energy requirement appears to be reasonable and conservative.

The values in Table 16 for industrial air and water pollution control were obtained by apportioning the total of 1.0 quad to agree with the air/water ratio corresponding to the DSI data (2) and (approximately) with the NCWQ (10) value for water pollution control (see Table 3, Section 4).

The value given in Table 16 for air pollution control at power plants was taken from the DSI study (2). A factor of two was used to obtain the error bounds. These are believed to be conservative in view of the good agreement among the estimates for the mid-1980's displayed in Table 3 and the fact that estimates for 1977 should be more accurate than those for the 1980's.

For powerplant thermal pollution control, the DSI (2) incremental (above the baseline) value of 0.086 quad in 1977 was used. The baseline value was estimated using the ERT (3) estimate of 0.03 quad for fossil-fueled plants in 1974. It was assumed that nuclear plants contribute the same amount, 0.03 quad, to the baseline value. This yielded an estimate of 0.06 quad for the baseline value, and a total (incremental plus baseline) energy requirement of 0.146 quad, which was rounded to 0.15 quad. A factor of two accuracy was assumed to obtain the error bounds. This factor for the error bounds is based on the agreement of the various estimates for 1983 listed in Table 2. The variation in estimates for 1977 should be much less, since there is less uncertainty about the capacity requiring control. However, this improvement is offset by the uncertainty in the baseline value.

The value listed for municipal wastewater treatment plants is based on the EEI (22) figure of 0.19 quad in 1977 and the ratio of electrical energy to total energy of 71% obtained in the Michigan study (4). It was shown previously that a factor of 2 yields reasonable error bounds for the EEI data. This factor was used to obtain the upper bound of 0.54 quad, and a factor of 3 was used for the lower bound. A higher factor was used for the lower bound because the EEI estimate is the highest of the values given in Table 5. The lower bound of 0.09 quad is then in the range of the lower estimates in Table 5.

The value of 0.1 quad for municipal solid waste disposal was obtained by rounding the values for landfilling listed in Table 6. The values were rounded upward as an extrapolation from 1970-73 to 1977. The error bounds were estimated based on the range of unit energy requirements for landfilling solid waste given by Hirst (8).

The total energy required for pollution control in all sectors is found to be 1.7 quad, with estimated error bounds of 0.8 quad to 3.4 quad. The nominal value of 1.7 quad represents approximately 2% of total U.S. energy consumption, with a range of 1% to about 4%. These values represent operating energy requirements only. Energy required for fabrication and installation of pollution control equipment (both new and replacement parts) is not included. According to data in Table 7, capitalization energy requirements, exclusive of replacement parts, would add an additional 0.2 quad to the total.

A comparison of pollution control energy requirements for 1985 is presented in Table 17. These data are less consistent and less reliable than the corresponding data in Table 16. In particular, no satisfactory estimate of energy required for industrial air pollution control is available. The value of 1.0 quad was obtained by extrapolation from the 1977 value of 0.65 quad (Table 16), assuming an annual growth rate of 5%. The very speculative nature of these estimates notwithstanding, the data indicate that energy requirements for pollution control at stationary sources in 1985 will amount to between 2% and 3% of total U.S. energy consumption in 1985.

DISTRIBUTION AMONG POLLUTANTS

The 1977 data from the previous section are regrouped according to pollutant type in Table 18. An additional calculation was required to apportion the energy for industrial air pollution control among the various pollutants. The DSI (2) breakdown of energy requirement by control device was used to obtain the following split: SO_x, 58%; particulate matter, 26%; others (NO_x, hydrocarbons, carbon monoxide), 16%.

TABLE 17. ENERGY REQUIRED FOR 1985 POLLUTION CONTROL, BY SECTOR[a]

Sector	Energy required, 10^{15} Btu	Percent of total energy requirement for pollution control at stationary sources	Percent of total U.S. energy requirement in 1985
Industry	-[b]	65	1.8
Air	1.0	-	-
Water	0.8	-	-
Total	1.8		
Powerplants	-	22	0.6
Air	0.4	-	-
Thermal	0.2	-	-
Total	0.6	-	-
Municipal wastewater treatment	0.35	13	0.4
Municipal solid waste disposal	0.0[c]	0[c]	0
Total	2.8	100	2.7

[a] Part of the information contained in this table is based on draft reports, which are subject to revision.

[b] Dashes indicate that a value was not determined or does not apply.

[c] It is assumed that energy recovery from incineration and recycling will offset the energy required for collection, transportation, and landfilling.

TABLE 18. ENERGY REQUIRED FOR 1977 POLLUTION CONTROL, BY POLLUTANT[a]

Pollutant type	Energy required, 10^{15} Btu	Percent of total energy requirement for pollution control at stationary sources
Water (chemical and biological)	-[b]	36
Industry	0.35	-
Municipal treatment plants	0.27	-
Power plants	Negligible	-
Total	0.62	-
Sulfur oxides	-	33
Industry	0.38	-
Power plants	0.18	-
Total	0.56	-
Particulate matter	-	10
Industry	0.17	-
Power plants	0.01	-
Total	0.18	-
Thermal	-	9
Power plants	0.15	-
Industry	Negligible	-
Total	0.15	-
Other air pollutants	-	6
Industry	0.10	-
Power plants	Negligible	-
Total	0.10	-
Municipal solid waste	0.10	6
Total	1.7	100

[a] Part of the information contained in this table is based on draft reports which are subject to revision.

[b] Dashes indicate that a value was not determined or does not apply.

From Table 18, the major energy requirements are for chemical and biological water pollution control and control of sulfur oxides, each of which accounts for about 35% of the total for pollution control at stationary sources.

Note that these results are based on the use of combustion modification techniques for the control of NO_x from combustion sources. Essentially no energy penalty is associated with these methods. However, if flue-gas treatment techniques for NO_x are required by future NO_x standards, a significant energy penalty could be incurred. For example, cost data on a sodium hypochlorite scrubbing process developed by Stanford Research Institute (36), indicate an energy penalty of 2.3% to 3.5% of fuel input. On the other hand, it is possible that such control methods will be capable of controlling both NO_x and SO_x. In this case, the additional energy penalty for NO_x control could be relatively small.

DISTRIBUTION WITHIN THE INDUSTRIAL SECTOR

The previous subsection showed (Table 16) that the industrial sector accounts for approximately 60% of the energy required for pollution control at stationary sources. In this section, the distribution of pollution control energy requirements within the industrial sector is given, and industries having a high priority in terms of reducing energy consumption for pollution control are identified.

Distribution of Pollution Control Energy Requirements Among SIC Categories

Energy requirements for industrial pollution control are given according to the two-digit SIC [Standard Industrial Classification (37)] scheme in both the DSI (2) and EEI (22) studies. The 1977 DSI data for water and air pollution control were combined to obtain the total energy required for industrial pollution control. The data are listed in order of decreasing energy requirement in Table 19. A similar listing of the EEI data is given in Table 20. Note that these two sets of data were obtained by entirely different methods and are, therefore, completely independent of each other.

TABLE 19. RANKED LISTING OF DSI DATA[a]

SIC	Name	Percent of 1977 energy requirement for pollution control in industrial sector	Cumulative %
33	Primary metals	36.0	36
28	Chemicals and allied products	15.4	51
20	Food and kindred products	11.3	63
29	Petroleum and coal products	7.2	70
26	Paper and allied products	5.1	75
51	Grain handling	5.0	80
24	Lumber and products	4.9	85
32	Stone, clay, and glass products	4.4	89
34	Fabricated metal products	2.0	91
22	Textile mill products	1.7	93
35	Machinery, except electrical	1.5	95
02	Feedlots	1.4	96
36	Electrical machinery	1.2	97
37	Transportation equipment	1.0	98
72	Dry cleaning	0.9	99
30	Rubber and plastic products	0.9	100
31	Leather and leather products	0.2	100
11/12	Coal cleaning	0.1	100

[a] Data from Reference 2; draft report subject to revision.

TABLE 20. RANKED LISTING OF EEI DATA[a]

SIC	Name	Percent of 1977 energy requirement for pollution control in industrial sector	Cumulative %
33	Primary metals	36.5	37
28	Chemicals and allied products	15.0	52
26	Paper and allied products	12.6	64
29	Petroleum and coal products	8.7	73
36	Electrical equipment	7.0	80
34	Fabricated metal products	4.3	84
32	Stone, clay, and glass products	3.6	88
37	Transportation equipment	3.5	91
20	Food and kindred products	2.1	93
35	Machinery, except electrical	1.6	95
39	Miscellaneous manufactures	1.2	96
12	Coal and lignite mining	0.9	97
24	Lumber and products	0.8	98
30	Rubber and plastic products	0.7	99
22	Textile mill products	0.6	99
14	Mining, nonmetallic minerals	0.2	99
13	Oil and gas extraction	0.2	99
25	Furniture and fixtures	0.2	100
27	Printing and publishing	0.1	10
99	Nonclassifiable	0.1	100
10	Metal mining	0.1	100
38	Instruments and related products	0.1	100
23	Apparel and related products	0.0	100
21	Tobacco manufactures	0.0	100
31	Leather and leather products	0.0	100
19	Ordnances and accessories	0.0	100
59	Retail stores	0.0	100
01	Agriculture	0.0	100

[a] Data from Reference 22.

The four industrial categories shown in Table 21 appear in the top five on both lists in Tables 19 and 20.

TABLE 21. INDUSTRIAL CATEGORIES IN TOP FIVE OF BOTH DSI AND EEI RANKINGS

SIC	Name	Percent DSI	Percent EEI
33	Primary metals	36.0	36.5
28	Chemicals and allied products	15.4	15.0
26	Paper and allied products	5.1	12.6
29	Petroleum and coal products	7.2	8.7
	Total	63.7	72.8

The seven categories shown in Table 22 are in the top ten on both lists in Tables 19 and 20.

TABLE 22. INDUSTRIAL CATEGORIES IN TOP TEN OF BOTH DSI AND EEI RANKINGS

SIC	Name	Percent DSI	Percent EEI
33	Primary metals	36.0	36.5
28	Chemicals and allied products	15.4	15.0
26	Paper and allied products	5.1	12.6
29	Petroleum and coal products	7.2	8.7
34	Fabricated metal products	2.0	4.3
32	Stone, clay, and glass products	4.4	3.6
20	Food and kindred products	11.3	2.1
	Total	81.4	82.8

The conclusion can be drawn that the industries within these seven categories account for approximately 80% of the total energy required for pollution control within the industrial sector. This amount is equivalent to approximately 50% of the energy required for pollution control at all stationary sources. The primary metals industry alone accounts for approximately 36% of the industrial total. Assuming the total is 1.0 quad (see Table 15), the value for primary metals is 0.36 quad. This is essentially the same as the value for power plants listed in Table 16 (0.34 quad).

In general, the two-digit SIC categories include a rather broad range of industries. For this reason, Battelle Columbus Laboratories (38) performed a resolution of the EEI data to four-digit SIC categories. The pollution control energy in each two-digit category was apportioned among the four-digit categories according to the ratio of total energy consumption of the four-digit category to that of the two-digit category. Clearly, this method is not strictly valid, but it does provide additional insight into the distribution of pollution control energy across the industrial sector.

A ranked listing of the EEI data based on the Battelle resolution is given in Appendix B. Since the Battelle study did not include the primary metals industry (SIC 33), this category was added to the Battelle listing, as were a number of other minor categories. Values of total energy consumption obtained from the Census of Manufactures (39) were used to apportion the pollution control energy among the four-digit categories.

Some idea of the validity of the Battelle resolution can be obtained from the following two examples. Assuming a total energy requirement for industrial pollution control of 1.0 quad (see Distribution Among Sectors), the Battelle method gives a value of 0.26 quad for the iron and steel industry. That is, the latter industry alone accounts for 70% of the total 0.365 quad in the primary metals category (SIC 33). The estimate given for the iron and steel industry in Reference 40 is 0.32 quad, based on 1973 production and compliance with 1983 Federal regulations. The two estimates agree to within 20%. On the other hand, the primary aluminum industry is a very energy-intensive industry that requires relatively little energy for pollution control. An estimate based on data from a study by A. D. Little, Inc. (41) gives a value of 5×10^{10} Btu/yr for pollution control in the primary aluminum industry, while the Battelle method yields 2.3×10^{13} Btu/yr--about 500 times greater.

Finally, it is of interest to note that of the 13 industries selected for in-depth studies by A. D. Little (41-53), only the textile industry (7) does not belong to one of the top seven two-digit SIC categories given above.

Other Indicators of Potential Energy Consumption for Pollution Control

According to the data in Table 16, air pollution control accounts for 65% of the energy required for industrial pollution control. From Table 18, control of sulfur oxides and particulate matter accounts for nearly 50% of the energy required for pollution control at stationary sources. Thus an alternative method of identifying industries that are potentially large consumers of energy for pollution control is based on emissions of sulfur oxides and particulate matter.

Ranked listings of industrial sources of sulfur oxides and particulate emissions (including powerplants) are given in Tables 23 and 24. These listings were obtained from Monsanto Research Corporation's computerized source assessment data base (54). The data base contains emissions data on more than 600 stationary sources and is periodically updated as part of the EPA source assessment program. The listings given in Tables 23 and 24 were terminated when the percentage of total mass emissions became less than 10^{-5}. In addition, certain open sources and residential sources were omitted from the listings. For this reason, the totals do not add to 100%. The May 1976 total mass of emissions in the data base is 6.84×10^{10} kg/yr for sulfur oxides and 1.82×10^{10} kg/yr for particulate matter.

The source assessment data base is incomplete in the area of metallurgical operations. For this reason, copper smelting (an important source of SO_x emissions) does not appear in Table 23. Copper smelting is estimated to account for 8% to 9% of total SO_x emissions in the United States (personal communication from E. L. Plyler, U.S. Environmental Protection Agency, January 14, 1977).

TABLE 23. INDUSTRIAL SOURCES OF SO_x EMISSIONS

Source	Percent of total SO_x emissions in data base[a,b]
Oil-fired industrial/commercial boilers	51.60000
Coal-fired steam electric utilities	27.00000
Coal-fired industrial/commercial boilers	4.90000
Oil-fired steam electric utilities	4.07000
Cement	1.08000
Natural gas processing	0.83500
Petroleum refining--catalytic cracking	0.71500
Wood processing--sulfite process	0.59200
Petroleum refining--crude distillation	0.40700
Coke manufacture	0.23600
Industrial/commercial space heating	0.21500
Fuel burning engines--reciprocating	0.21200
Brick kilns and driers	0.20700
Petroleum refining--vacuum distillation	0.14700
Wood processing--Kraft or sulfate process	0.09610
Petroleum refining--flares	0.09090
Sulfuric acid	0.08270
Pig iron production	0.08040
Primary lead smelting and refining	0.06140
Petroleum refining--sulfur plant	0.04210
Glass industry	0.03860
Secondary lead smelting and refining	0.03210
Barium carbonate	0.02970
Municipal incineration	0.02770
Mineral wool	0.02470
Fuel burning engines--turbine	0.01640
Asphalt paving--hot mix	0.01490
Incineration of "Type 1" waste	0.01220
Incineration of "Type 6" waste	0.00879
Primary zinc smelting	0.00840
Barium sulfate--pigment	0.00720
Wood processing--Neutral sulfite semi-chemical	0.00712
Petroleum refining--asphalt plant	0.00695
Petroleum refining--catalytic reforming	0.00501
Petroleum refining--catalytic hydroefining (HDS)	0.00368
Gas-fired industrial/commercial boilers	0.00359
Incineration of "Type 2" waste	0.00336
Refuse incineration/pyrolysis--steam generation	0.00318
Incineration of "Type 0" waste	0.00293
Carbon disulfide	0.00242
Phthalic anhydride--*o*-xylene	0.00218
Sodium silicates	0.00191
Sewage sludge incineration	0.00166
Calcium carbide	0.00162
Explosives burning	0.00157
Polystyrene resin	0.00142
Vitreous kaolin products	0.00131
Gas-fired steam electric utilities	0.00122
Open burning of industrial waste	0.00120
Cyclohexane	0.00113
Amino resins	0.00113
Incineration of "Type 3" waste	0.00094
Dimethyl terephthalate	0.00082
Carbon black--furnace	0.00065
Leather	0.00064
Asphalt paving--dryer drum process	0.00042
Coal cleaning plants--thermal drying	0.00035
Sodium sulfite	0.00029
Naphthalene--coal tar	0.00029
Sodium chromate and sodium dichromate	0.00010
Hospital waste incineration	0.00009
Gas-fired air conditioning	0.00008
M-xylene	0.00005
Nitrocellulose	0.00004
Polysulfide rubber	0.00003
Petroleum refining--aromatics/isomerization	0.00003
Petroleum refining--alkylation	0.00002
Isocyanates	0.00001
Chromium oxide--inorganic pigment	0.00001
Electrical equipment winding reclamation	0.00001

[a] The data base is incomplete in the area of metallurgical operations, since these operations were originally outside the scope of the data base.

[b] Percentages are reproduced from computer printouts without rounding; no inference regarding accuracy of the data should be made on the basis of these listings.

TABLE 24. INDUSTRIAL SOURCES OF PARTICULATE EMISSIONS

Source	Percent of total SO_x emissions in data base[a,b]
Coal-fired steam electric utilities	33.30000
Oil-fired industrial/commercial boilers	19.90000
Coal-fired industrial/commercial boilers	6.51000
Cement	4.82000
Steel production	2.89000
Lime kilns	1.71000
Wood processing--kraft and sulfate process	1.52000
Municipal incineration	1.25000
Coke manufacture	1.20000
Mineral wool	0.91500
Primary aluminum production	0.79400
Ferroalloy production	0.75900
Refractories	0.73400
Charcoal manufacture	0.62700
Malt beverage production	0.59600
Gypsum	0.54600
Wood waste incineration	0.52600
Oil-fired steam electric utilities	0.46600
Gas-fired industrial/commercial boilers	0.42700
Aluminum oxide--alumina	0.30900
Incineration of "Type 1" waste	0.27500
Industrial/commercial space heating	0.26400
Asphalt paving--hot mix	0.26300
Secondary aluminum production	0.24100
Petroleum refining--catalytic cracking	0.22800
Incineration of "Type 6" waste	0.19800
Petroleum refining--crude distillation	0.19100
Incineration of "Type 2" waste	0.15200
Ammonium nitrate	0.14400
Wood processing--sulfite process	0.13700
Glass industry	0.13600
Ammonium phosphates	0.13300
Potash--potassium salts	0.13000
Asphalt roofing	0.12700
Polyvinyl chloride	0.11900
Gas-fired steam electric utilities	0.11500
Phosphate rock--drying, grinding, calcining	0.11300
Vitreous kaolin products	0.11100
Nylon 66	0.10500
Soap and detergents	0.10100
Fuel-burning engines--reciprocating	0.09830
Fuel-burning engines--turbine	0.09690
Sewage sludge incineration	0.07470
Open burning of industrial waste	0.07210
Wet corn milling	0.07190
Petroleum refining--vacuum distillation	0.06890
Refuse incineration/pyrolysis--steam generation	0.06690
Calcium carbide	0.06680
Incineration of "Type 0" waste	0.06610
Ammonium sulfate	0.06020
Nylon 6	0.04990
Sodium carbonate--natural	0.04560
Incineration of "Type 3" waste	0.04260
Coal cleaning plants--thermal drying	0.03980
Zinc oxide--pigment	0.03890
Calcium chloride	0.03780
Cotton gins	0.03760
Vegetable oil milling	0.03550
Superphosphate--normal	0.03530
Cottonseed oil milling	0.03380
Steel foundries	0.03280

See footnotes at end of table, p. 47.

(continued)

TABLE 24 (continued)

Source	Percent of total SO_x emissions in data base[a,b]
Petroleum refining--asphalt plant	0.03550
Sodium tripolyphosphate	0.03130
Primary copper smelting	0.03070
Sugar processing	0.02990
Carbon black--furnace	0.02560
Titanium dioxide--pigment	0.02350
Primary lead smelting and refining	0.01760
Magnesium compounds--carbonate, chloride, oxide and hydroxide	0.01670
Distilled liquor	0.01450
Abrasive products	0.01420
Hydrofluoric acid	0.01290
Brick kilns and dryers	0.01280
Sodium sulfate--natural process only	0.01270
Fertilizers--bulk blending plants	0.01210
Boric acid and borax--sodium tetraborate	0.01200
Urea	0.01150
Perlite manufacturing	0.01060
Fertilizer mixing--ammoniation--granulation plants	0.01030
Gas-fired air conditioning	0.01000
Secondary lead smelting and refining	0.00945
Petroleum refining--catalytic reforming	0.00915
Phosphoric acid--thermal process	0.00839
Incineration of "Type 5" waste	0.00777
Sodium carbonate--synthetic	0.00776
Solvent evaporation--surface coating--auto painting	0.00762
Exfoliated vermiculite	0.00749
Asphalt paving--dryer drum process	0.00747
Aluminum sulfate	0.00661
Petroleum refining--catalytic hydrorefining (HDS)	0.00660
Covered wire incineration	0.00598
Zinc galvanizing operations	0.00594
Sodium silicates	0.00527
Coal-cleaning plants--pneumatic	0.00506
Calcium phosphate	0.00443
Tobacco	0.00436
Sodium sulfide	0.00430
Dimethyl terephthalate	0.00403
Polyethylene resin--low density	0.00329
Amino resins	0.00318
Cumene	0.00315
Adipic acid	0.00293
Fruit and vegetable canning	0.00284
Food preparation	0.00274
Asbestos products	0.00267
Aluminum hydroxide	0.00264
Drum incineration	0.00261
Paint manufacturing	0.00261
Leather	0.00242
Fruit and vegetable freezing	0.00234
Explosives burning	0.00204
Potassium sulfate	0.00201
Isocyanates	0.00198
Electrical equipment winding reclamation	0.00172
Calcium carbonate	0.00165
Polystyrene resin	0.00161
Autobody incineration	0.00143
Printing ink	0.00124
Incineration of "Type 4" waste	0.00122
Sodium sulfite	0.00111

See footnotes at end of table, p. 47.

(continued)

TABLE 24 (continued)

Source	Percent of total SO_x emissions in data base[a,b]
Fertilizer mixing--liquid mix plants	0.00099
Sodium chlorate	0.00097
Production of lead acid batteries	0.00085
Sodium chromate and sodium dichromate	0.00080
Cresol--synthetic	0.00072
Phthalic anhydride--*o*-xylene	0.00061
Carbon disulfide	0.00061
Meat smokehouses	0.00037
Miscellaneous sodium compounds	0.00031
Styrene	0.00029
Sodium hydrosulfite	0.00023
Sodium thiosulfate--sodium hyposulfite	0.00031
Cadmium pigments--cadmium sulfide, sulfoselenide, lithopone	0.00020
Lead oxide--red lead and litharge--pigments only	0.00020
Iron chloride--ferric	0.00019
Manganese sulfate	0.00019
Copper sulfate--pentahydrate	0.00019
Vinyl acetate--from acetylene	0.00018
Zinc chloride--50-degree Baume	0.00018
Aluminum chloride--anhydrous	0.00017
Lead carbonate and sulfate--white lead	0.00015
Sulfated ethoxylates--AEOS	0.00011
Potassium permanganate and manganese dioxide	0.00010
Oxalic acid	0.00009
Nickel sulfate	0.00005
Arsenic trioxide	0.00005
Cobalt compounds--acetate, carbonate, halides, etc.	0.00005
Sodium nitrate	0.00004
Sodium fluoride	0.00004
Petroleum refining--aromatics/isomerization	0.00003
Brake shoe debonding	0.00003
Polyamide resins	0.00003
Phthalic anhydride--naphthalene	0.00003
Lindane	0.00003
Barium sulfate--pigment	0.00002
Acetic anhydride	0.00002
Oxo-mixed linear alcohols	0.00002
Oxo process	0.00002
Lithium salts--lithium carbonate and lithium hydroxide	0.00002
Secondary magnesium smelting	0.00002
Nickel compounds--except nickel sulfate	0.00001
Sodium arsenite	0.00001
Silver compounds--NO_3, difluoride, fluoroborate, SO_4	0.00001
Tin compounds--halides, oxides, sulfates, others	0.00001
Lead chromate--chrome yellow and orange	0.00001
Petroleum refining--alkylation	0.00001
Chromic acid	0.00001

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[a] The data base is incomplete in the area of metallurgical operations, since these operations were originally outside the scope of the data base.

[b] Percentages are reproduced from computer printouts without rounding; no inference regarding accuracy of the data should be made on the basis of these listings.

The listings in Tables 23 and 24 represent estimates of actual emissions; hence, no distinction is made between controlled and uncontrolled emissions. In addition, the listings do not take into account distributions of plant size and geographical location.

However, the emissions are concentrated in so few sources that these considerations are of minor importance. Thus industrial/commercial boilers and steam electric utilities account for nearly 90% of sulfur oxides emissions and over 60% of particulate emissions. Industrial boilers account for approximately 68% of sulfur oxides emissions and 85% of particulate emissions in the industrial/commercial boiler category.

If it is assumed that the energy that will be required for control of sulfur oxides is proportional to mass emissions of sulfur oxides, the data in Table 23 can be used to show that 76% of the energy required for industrial sulfur oxides control will be for control of boiler emissions. The remaining 24% will be for control of nonboiler sources of sulfur oxides emissions. Thus, of the 0.38 quad listed in Table 18 for control of sulfur oxides in the industrial sector, 0.29 quad is associated with boiler emissions and 0.09 quad is associated with control of other industrial emission sources.

A similar estimate for particulate emissions indicates that 37% of the industrial energy requirement for particulate control is associated with boiler emissions. Thus, of the 0.17 quad listed in Table 18 for control of particulate matter in the industrial sector, 0.06 quad is associated with boiler emissions and 0.11 quad is associated with control of other industrial emission sources.

The above value of 0.06 quad for control of particulate emissions from industrial boilers can be compared with the value of 0.01 quad listed in Table 18 for control of particulate emissions from electric power plants. Since the total annual mass of particulate emissions from power plants is greater than that from industrial boilers (according to Table 24), the above energy requirements appear to be inconsistent. The discrepancy may simply be a reflection of the rather crude approximations that were employed to arrive at the value for industrial boilers. However, there are several factors that would tend to increase the energy requirement for industrial boilers relative to utility boilers:

- The value of 0.01 quad for power plants is based on the DSI (2) estimate which assumes that SO_x scrubbers will be used for particulate control. Thus part of the energy required for particulate control at power plants is charged against SO_x control.

- The DSI estimate assumes that powerplants not required to use SO_x scrubbers will employ electrostatic precipitators for particulate control. Precipitators have low energy requirements relative to other particulate control devices (see Figure 3). Smaller industrial boilers, on the other hand, are more likely to employ cyclones, bag filters, or wet scrubbers, which are more energy intensive but less capital intensive than precipitators.

- Industrial boilers tend to be operated less efficiently than utility boilers. In particular, higher excess air firing in industrial boilers may generate larger volumes of flue gas to be treated and, hence, larger energy requirements.

Total water intake can be used to estimate relative potential energy requirements for water pollution control. A ranked listing of total water intake by two-digit SIC categories is given in Table 25. The good agreement with the rankings of the DSI and EEI data (Tables 19 and 20) is evident. The primary metals industry again tops the list. The iron and steel industry alone accounts for 86% of the total water intake in the primary metals category (10).

TABLE 25. INDUSTRIAL WATER INTAKE[a]

SIC	Name	Percent of total industrial water intake	Cumulative percent
33	Primary metals	32.9	33
28	Chemicals and allied products	27.8	61
26	Paper and allied products	16.1	77
29	Petroleum and coal products	8.6	85
20	Food and kindred products	5.4	91
37	Transportation equipment	1.6	92
32	Stone, clay, and glass products	1.2	95
35	Machinery, except electrical	1.1	96
24	Lumber and wood products	1.1	97
30	Rubber and plastic products	1.0	98
34	Fabricated metal products	0.7	99
36	Electrical equipment supplies	0.7	100
38	Instruments and related products	0.3	100
39	Miscellaneous manufacture	0.1	100

[a] Data from Reference 10; draft report subject to revision.

SECTION 6

ALTERNATIVE POLLUTION CONTROL STRATEGIES

The purpose of this section is to consider means by which pollution control objectives can be achieved while reducing the energy required for control. The data contained in Figures 1, 2, and 3 provide some general guidelines for the selection of pollution control equipment that will tend to minimize energy consumption. However, the specification of less energy-intensive overall control strategies is highly dependent on the process to be controlled. Hence this discussion is limited to those industries for which in-depth analyses are available. Fortunately, this category includes powerplants and the iron and steel industry, which together account for approximately 40% of the energy required for pollution control at stationary sources.

POWERPLANTS

Control of Sulfur Oxides

The ERT study (3) investigated the energy requirements for the following seven SO_2 control scenarios:

1. Scrubber and low-sulfur fuel: Compliance through the use of only low-sulfur fuel and scrubbers.

2. Coal washing: Coal washing used for high-sulfur coal wherever it can replace scrubbers.

3. BACT: Pre-1975 units follow Scenario 1 and post-1974 units apply "best available control technology," which is defined as one-half of the oil desulfurized and one-half of the coal washed, with all new units scrubbed.

4. SCS-LSA: Same as Scenario 1, except that supplementary control systems (SCS)[a] are permitted in low-sulfate areas (but not in high-sulfate areas such as the East Coast).

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[a] Supplementary control systems are systems designed to temporarily reduce pollutant emissions during periods of unfavorable meteorological conditions to avoid exceeding ambient air quality standards. In the case of SO_x emissions from powerplants,

5. SCS-E: Same as Scenario 1, but supplementary control systems are permitted everywhere.

6. Tall stacks-LSA: Same as Scenario 1, but post-1974 units outside the East Coast and other high-sulfate States can employ tall stacks.

7. Tall stacks-E: Same as Scenario 1, but post-1974 units can employ tall stacks everywhere.

The effects of the following variables were studied:

- Type of control technology employed
- Air quality goal to be achieved
- Degree of plant conversion to coal
- Growth rate of the industry

The results of the calculations are shown in Table 26, with the energy requirement expressed as percent of total 1983 fossil-fuel energy input to all powerplants in the United States. The range of values for Scenarios 3 through 7 results from varying the latter two of the above variables (plant conversion and growth rate). Compliance with primary and secondary ambient air quality standards is assumed for the low-energy scenarios. For Scenarios 1 and 2, the latter three of the above variables are responsible for the range of values in Table 26. The low values are associated with compliance with primary air quality standards only. The high values represent compliance with ambient air quality standards, new source performance standards, State implementation plans, and nondeterioration regulations.

The results in Table 26 indicate that significant energy savings are possible through the use of supplementary control systems. For example, the attainment of primary and secondary ambient air quality standards by means of supplementary control systems (Scenario 5) requires about one-half as much energy as is required using scrubbers and low-sulfur fuel (Scenario 1). However, supplementary control systems are not capable of meeting new source performance standards. In addition, they do not significantly reduce atmospheric sulfate levels.

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available techniques include switching from high-sulfur to low-sulfur fuel (fuel switching) and importing electricity from regions of the electric grid not affected by adverse meteorological conditions (load shifting).

TABLE 26. ENERGY REQUIREMENTS OF POWERPLANT SO_2 CONTROL SYSTEM SCENARIOS[a]

Scenario	Energy requirements, percent of total fossil-fuel input		
	Low	Average	High
High-energy scenarios:			
1. Scrubbers and low-sulfur fuel[b]	2.2	3.8	5.5
2. Coal cleaning, some scrubbers, low-sulfur fuel[b]	3.2	4.8	6.4
3. BACT[c]	6.7	7.1	7.5
Low-energy scenarios[d]:			
4. SCS in low-sulfate areas	2.2	2.4	2.5
5. SCS everywhere	1.4	1.6	1.8
6. Tall stacks in low-sulfate areas	2.2	2.4	2.4
7. Tall stacks everywhere	1.8	1.9	2.1

[a] Data from Reference 3.

[b] Scenarios 1 and 2 energy requirement ranges based on attainment to varying degrees of all air quality regulations.

[c] Scenario 3 is based on BACT, which is defined for new units as one-half of all oil desulfurized, and scrubbers on new units. Old units comply with Scenario 1.

[d] Scenarios 4 through 7 based on attaining air quality standards but not new source performance standards, State implementation plans, nondeterioration, and BACT.

An examination of the unit energy requirements given in Section 4, Unit Energy Requirements of Pollution Control Strategies, also leads to the conclusion that there are few options for reducing energy consumption for SO_2 control other than supplementary control systems. Coal cleaning (physical) has an energy penalty of 7%, compared with 3.5% to 10% for flue-gas scrubbing. Oil desulfurization has an energy penalty of 3% to 6% according to the Michigan (4) and ERT (3) studies, and 1.2% to 8.6% according to the DSI study (2). The higher values correspond to higher-sulfur-content oils. The average value for oil desulfurization is about 5%. Hence, only for the lower-sulfur oils (less than about 1.0% sulfur) is there a significant energy advantage in oil desulfurization over flue-gas scrubbing. Similarly, use of western coal entails a penalty of 4.5% [mostly for transportation (3)], which is in the same range as flue-gas scrubbing.

One method identified in the ERT (3) study for reducing energy consumption for SO_2 control is coal blending. This method involves blending low-sulfur western coal and high-sulfur eastern coal so that the average sulfur content of the blended coal (e.g., one-third western coal, two-thirds eastern coal) is low enough to meet environmental standards. Since this method uses less western coal than does complete substitution of western coal for eastern coal, it entails a smaller energy penalty for transportation of western coal. In addition, the heating value of the blended coal is higher than that of western coal. The estimated energy penalty for coal blending is 0.5% to 2.0% of powerplant fuel input, which is significantly lower than the energy penalty for flue-gas scrubbing (3).

A control method that holds promise of significant energy savings in the future is fluidized-bed combustion. Although an energy penalty of 5% is given for fluidized-bed combustion in the ERT study (3) (see Table 8), the efficiency of this method is expected to improve as the technology develops (55). The thermal efficiencies projected for first-generation and later-generation fluidized-bed boilers are compared with that of a conventional boiler equipped with a scrubber in Table 27. The pressurized fluidized-bed system appears to be very promising, indeed. However, such systems are not expected to be available for commercial operation until the late 1980's, and then only for new units, since retrofitting would require replacement of essentially the entire boiler (56).

TABLE 27. PROJECTED EFFICIENCIES OF FLUIDIZED-BED POWERPLANTS[a]

Boiler type	Overall thermal efficiency, % First generation	Ultimate
Atmospheric fluidized bed	36	40
Pressurized fluidized bed	38	47
Conventional with flue-gas scrubbing	37	37[b]

[a] Data from Reference 55.

[b] No improvement in the energy efficiency of flue gas scrubbing is assumed. A 60% improvement in scrubber energy efficiency would be required to equal the projected overall efficiency of atmospheric fluidized-bed boilers.

The atmospheric fluidized-bed boiler appears to be much less promising than the pressurized fluidized-bed boiler. In fact, improvements in scrubber energy efficiency and conventional boiler efficiency could conceivably offset the projected improvement in atmospheric fluidized-bed powerplant efficiency. However, an additional advantage of fluidized-bed combustion is its potential for controlling NO_x as well as SO_x.

Significant improvement in the energy efficiency of flue-gas desulfurization systems may be possible by improved engineering design, since the importance of minimizing energy consumption in the design of such systems has only recently become apparent. The following suggestions for reducing scrubber energy consumption have been made (personal communication from E. L. Plyler, U.S. Environmental Protection Agency, Research Triangle Park, NC, January 14, 1977):

- Use of a low-energy particulate control device, such as an electrostatic precipitator, followed by a low-pressure-drop scrubber, such as a spray tower.
- Determination of minimum stack gas reheat requirements; in some cases, flue gas bypass can be used for reheat.
- Improvement of limestone utilization; this would reduce both preplant and postplant energy requirements. It could also reduce inplant energy requirements by lowering power consumption for pumping.

The energy required for flue-gas desulfurization could also be lowered by partial removal of sulfur from coal before combustion. However, due to the 7% energy penalty for coal cleaning noted above, there would be no overall energy savings with this strategy

Other aspects (economic, technical, environmental, etc.) of the alternatives for SO_x control are discussed at some length in Reference 55.

Thermal Pollution Control

Two methods of conserving energy in the control of thermal pollution are identified in the ERT study (3):

- Use of less energy-intensive, closed-cycle cooling systems.
- Waste heat utilization.

The data in Table 8 indicate that cooling ponds and spray ponds are significantly less energy intensive than mechanical forced-draft cooling towers. The major drawback of cooling ponds is the large amount of land required (a cooling pond is in reality an artificial lake). Hence their applicability is limited to locations where sufficient land is available. Spray ponds require more operating energy than cooling ponds to operate the sprayers. However, they can reduce the land area required by a factor of up to 10 (12).

Approximately 65% of the energy input to electric powerplants is rejected as low-temperature waste heat. Hence utilization of this heat would conserve energy as well as reduce the need for thermal pollution control. Integrated systems have been proposed (and in some cases constructed) that utilize powerplant waste heat for agriculture and aquaculture (12, 57), sewage treatment (58), industrial process steam (12), and commercial and residential space heating and cooling (12, 59). Karkheck, et al. (59), have estimated that use of powerplant waste heat for space heating could save up to 5 quad annually in the United States. Major problems include powerplant location (plants must be located close to waste heat users), large capital requirements, and the fact that in many applications only a small fraction of the total waste heat can be utilized (12). Waste heat utilization is not expected to have a significant impact on thermal pollution control in the period 1977 to 1985 (12).

Particulate Control

No alternatives to electrostatic precipitators have been identified that will reduce the energy required for control of particulate emissions from powerplants. However, energy requirements for this purpose are relatively small (0.2% of plant fuel input) compared with the energy required for SO_x and thermal pollution control. One alternative to flue-gas treatment for particulate (and SO_x) control is combustion of solvent-refined coal (SRC). SRC is to have a low enough ash content (less than 0.1% ash) to eliminate the need for removal of particulate matter from flue gases. The low sulfur content of SRC will likewise eliminate the need for flue-gas desulfurization. However, it is estimated by Schmid (60) that the thermal efficiency of the SRC process will be 74%. The corresponding 26% energy penalty for particulate and SO_x control by SRC thus is about five times the energy penalty for control of these pollutants by flue-gas treatment.

THE IRON AND STEEL INDUSTRY

Energy requirements for pollution control in the iron and steel industry were determined through an in-depth study by Resource Planning Associates (RPA) (40). The energy requirements, based on 1972 production levels and compliance with all existing pollution control legislation, are summarized in Table 28.

Possible energy savings resulting from various alternatives were also investigated by RPA. The study included process modifications as well as alternative control methods. The results are summarized in Table 29.

The potential exists for improved efficiency of air pollution control systems through the use of more efficient fan blades. The overall mechanical efficiency of a motor/blower combination is thought to be raised from 65% to 74% by changing the blades in fabric filter and electrostatic precipitator centrifugal blowers from radial tip to solid airfoil blades. It was also assumed (40)

TABLE 28. ANNUAL POLLUTION CONTROL ENERGY REQUIREMENT FOR THE IRON AND STEEL INDUSTRY[a]

	Pollution control energy requirement, 10^{12} Btu				
Unit process	Air	Water	Preplant	Postplant	Total
Materials preparation:					
Ore yard	-[b]	-	-	-	-
Coal yard	0.85	-	0.07	-	0.92
Scrap yard	-	-	-	-	-
Limestone yard	-	-	-	-	-
Sintering	10.67	2.22	0.61	0.01	13.51
Coking	31.10	7.90	4.60	0.48	44.08
Iron and steel making:					
Direct reduction	-	-	-	-	-
Blast furnace	48.30	13.97	5.56	0.59	68.42
Electric arc furnace	20.39	1.89	1.63	0.09	24.00
Open hearth furnace	46.65	1.94	4.79	0.14	53.52
Basic oxygen furnace	29.80	4.97	2.17	0.35	37.29
Vacuum degassing	-	3.09	0.13	-	3.22
Ingot casting	-	-	-	-	-
Continuous casting	0.21	1.37	0.19	0.01	1.78
Forming and finishing:					
Soaking pits	-	-	-	0.10	0.10
Scarfing	1.70	-	0.03	-	-
Hot forming:	-	-	-	-	1.73
Primary	-	12.32	0.36	0.20	12.88
Section	-	7.73	0.74	-	8.47
Flat plate	-	0.91	1.75	0.03	2.69
Other flat	-	23.29	0.58	-	23.87
Mills:					
Structural and rail	-	-	-	0.11	0.11
Pipe and tube	-	3.54	0.14	-	3.68
Bar	-	-	0.03	0.06	0.09
Wire rod	-	1.35	-	-	1.35
Strip	-	-	-	-	-
Cold drawing bars	-	-	-	-	-
Pickling	0.15	0.97	0.91	-	2.03
Cold rolling	-	3.00	0.68	0.02	3.70
Hot coating:	-	-	0.06	-	0.33
Galvanized	-	0.27	-	-	-
Terne and alumized	-	-	-	-	-
Cold coating:	-	-	0.06	-	0.31
Tin	-	0.18	-	-	-
Chrome	-	0.07	-	-	-
Zinc	-	-	-	-	-
Steam and electricity generation	6.60	8.16	0.06	0.11	14.93
Total	196.5	99.1	25.2	2.3	323.0

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[a] Data from Reference 40.

[b] Dashes indicate zero or negligible energy requirments or that no value is applicable.

TABLE 29. SUMMARY OF AIR AND WATER POLLUTION CONTROL ENERGY SAVINGS FROM SELECTED ALTERNATIVES[a]

Selected alternatives for air and water pollution control	Savings from base case,[b] trillions of Btu's	Percent of pollution control energy requirement
Air pollution control (base case equals 195 trillion Btu's/yr):		
Control system efficiency: More efficient fan blades	19.4	6
Production process:		
Replace all open hearth furnaces with conventional basic oxygen furnaces	29.4	9
Replace all open hearth furnaces with suppressed combustion basic oxygen furnaces	34.1	11
Water pollution control (base case equals 99 trillion Btu's/yr):		
Wastewater flow:		
Dry air pollution control equipment (for electric arc, open hearth, and basic oxygen furnaces)	4.4	1.4
Split recycle in hot-forming section	0.8	0.3
Alternative thermal control technology:		
Cooling pond	36.3	11
Spray pond	33.3	10
Natural draft cooling tower	5.9	1.8

[a] Data from Reference 40.

[b] Each saving must be considered individually since they are not cumulative.

that radial tip blades could be used in high-energy scrubber blowers to improve overall motor/blower efficiency to 69%. Before such a change could be made, however, blade strength and rigidity problems, which have resulted in damage to the fan housing, must be resolved.

The industry trend toward the basic oxygen furnace (BOF) as opposed to the open-hearth furnace will further reduce the energy required for pollution control. The conventional BOF furnace (open-hood venting) requires about 37% of the energy/ton of production required by the open-hearth furnace for pollution control. Furthermore, a suppressed-combustion hooding system (closed-hood venting) on a BOF reduces the exhaust rate by 80%. (The flow reduction applies to the main exhaust only. Other flows, that is, reladle and fugitive, are not affected by use of closed hoods.) Thus the BOF with suppressed-combustion hooding requires only about 27% of the energy/ton of steel required by the open-hearth furnace for pollution control.

Closed-hood systems also allow recovery of carbon monoxide from the exhaust gas (40, 42, 61). The CO recovered from two 250-ton furnaces can be used as fuel to supply the equivalent of 17,600 hp continuously (61). Although CO recovery has been practiced in Japan and Europe for years, the exhaust gas is presently flared in all U.S. plants (40, 61). The additional energy that could be saved by CO recovery is not included in Table 29.

Additional savings (not included in Table 29) in the energy required for air pollution control could be realized by replacing high-energy scrubbers with fabric filters or electrostatic precipitators for control of particulate matter. Areas where such replacements are possible include the following:

- Main exhaust from electric-arc, open-hearth, and basic-oxygen furnaces.
- Main exhaust from sintering windbox.
- Main exhaust from scarfing operation.
- Coke-pushing operation.

There appears to be some question, however, as to whether current air pollution regulations can be met with fabric filters and electrostatic precipitators in these applications (40) (personal communication with Howard Lacy, American Iron and Steel Institute, 20 January 1976).

Substitution of dry air pollution control methods for scrubbers in the above applications would also reduce the volume of wastewater requiring treatment. As indicated in Table 29, replacement of scrubbers on furnace exhaust streams alone would reduce the energy required for water pollution control by 4.4×10^9 Btu/yr.

Wastewater flow rates can also be reduced by appropriate process modifications. For example, use of split recycling in the hot forming operation would save an estimated 0.8×10^9 Btu/yr in the energy required for wastewater treatment (40). In a split recycle (as opposed to a once-through system), part of the wastewater is recycled to the process with minimal or no treatment. Effluent from one process step can also be recycled to another process step that does not require high-quality water. For example, hot rolling mill wastewater can be recycled to the cold rolling mill without extensive treatment (40). [Although such recycling has been successfully demonstrated in the industry, accurate estimates of the potential energy savings cannot be calculated because of the importance of individual plant configurations to the quality of water required in downstream processes and the possibilities for recycling (40)].

Other process modifications with the potential to reduce wastewater flow rates have been identified, but estimates of potential energy savings are not available. These include the following (40):

- Improved squeeze roll use
- Use of cascade rinsing
- Use of cold-rolling recirculation

The following alternative wastewater treatment strategies have been suggested for reducing energy requirements (40):

- Substitution of a biological filter, followed by deep-bed filtration for the aerated settling process in treating sinter plant wastewater.

- Combination of wastewater streams in a central facility for terminal treatment.

- Substitution of dry well injection or neutralization, aeration, and sedimentation for acid recovery in the treatment of pickling wastes.

Estimates of the potential energy savings with the above methods have not been reported (40).

The data in Table 29 indicate that cooling ponds, spray ponds, and natural-draft cooling towers are less energy-intensive methods of thermal pollution control than mechanical forced-draft cooling towers, which were assumed for the base case. The reason that natural-draft towers are less energy intensive than forced-draft towers in this application (as opposed to powerplants, where forced-draft towers are less energy intensive) is that there is no energy penalty as a result of increased turbine back pressure in this case. Natural-draft towers, however, require a greater capital investment than do forced-draft towers.

If all the options listed in Table 29 were adopted, the total energy savings would amount to about 20% of the total energy required for pollution control in the iron and steel industry (assuming natural-draft cooling towers were used for thermal pollution control). As noted in the above discussion, a number of other alternatives exists which, if adopted, could result in additional savings in pollution control energy requirements.

A number of other process modifications designed to conserve energy, but whose primary purpose is not to reduce pollution control energy requirements, have been reported in the literature (61). These process modifications are summarized in Table 30. In addition to these modifications, there are a number of high-temperature waste streams within the steel-making operation from which thermal energy can be recovered. Examples of unit processes with such waste streams are steel reheating furnaces, soaking pits, annealing furnaces, blast furnace stoves, coke ovens, and open-hearth furnaces (61). Regenerators, recuperators, and

TABLE 30. SOME POTENTIAL ENERGY-CONSERVING PROCESS MODIFICATIONS IN THE IRON AND STEEL INDUSTRY[a]

Process modification	Environmental effects	Effect on process energy requirements
Formcoke cokemaking process.	Can be operated as a fully enclosed, continuous process, thereby minimizing air and water pollution problems.	May require more or less energy, depending on circumstances. Principal advantage is use of lower-grade coals.
Hot coal charging of coke ovens.	Data are not available to make an evaluation.	Should require less energy, since moisture is removed from coal at lower temperature. However, operating data are not available for evaluation.
Dry quenching of coke.	May increase particulate control problems because of very dry, dusty nature of the coke.	The thermal energy content of the hot coke (1.1×10^6 Btu/ton) can be recovered.
Pulverized coal injection into blast furnace.	Particulate emissions from pulverizer controlled by cyclones and bag filters. Reduced demand for coke would reduce emissions from coke plant, which are controlled with sheds or spot cars and high-energy scrubbers. Net effect should be fewer emissions and lower energy requirement for control.	Energy input to blast furnace is increased; may save energy at coke plant. Principal advantage is use of nonmetallurgical grade coal.
Conversion of blast furnace top pressure to electricity.	No effect at steel plant; reduced emissions at powerplant because of reduced demand.	Potential power recovery is 3 MW to 5 MW per 100,000 scfm flow.
Evaporative cooling of blast furnace.	Closed loop system eliminates thermal pollution and decreases water consumption.	Generates low-pressure steam that can be used for space heating. Natural convection system eliminates pumping requirements.
External desulfurization.	Small increase in air and water pollution control requirements; decrease in solid waste generation because of decreased slag production.	Main advantage is that high-sulfur metallurgical coal can be used without incurring an energy penalty.
Continuous casting.	None reported.	Requires about 50% less energy than conventional rolling and 20% less liquid steel.
Direct rolling.	None reported.	No reheating of intermediate product saves 2.3 million Btu/ton steel.
Induction slab heating.	Eliminates pollution from combustion of gas or oil in conventional slab reheat furnace.	Requires 35% more energy than conventional furnace. Substitutes electricity for gas or oil.
MONOBEAM® slab reheating furnace.	Small decrease in pollutants from fuel combustion because of lower energy requirement per unit weight of steel produced.	Requires 5% less energy per unit weight of steel produced because of higher throughput.
Evaporative cooling of reheat furnace skid system.	None reported.	Generates low-pressure steam that can be used for space and process heating.
Direct-fired batch annealing.	None reported.	Requires 15% to 30% less energy than radiant tube batch annealing.
Direct reduction of iron ore.	Requires about 15% more energy for pollution control than conventional blast furnace operation.	Requires about 60% more energy than conventional blast furnace. Main advantage is use of nonmetallurgical grade coal.

[a] Data from References 42 and 61.

waste heat boilers are commonly used for waste heat recovery in the steel industry (61). As the cost of energy continues to increase, additional opportunities for economical waste heat recovery in the industry should become available.

NITRIC ACID PLANTS

Nitric acid manufacturing plants represent the only noncombustion stationary source type for which new source performance standards for nitrogen oxides emissions have been promulgated by EPA. The tail gas from the adsorber in nitric acid plants typically contains between 1,500 and 5,000 ppm NO_x. A number of methods are available for control of the NO_x emissions, five of which were studied in the A. D. Little report on the fertilizer industry (53):

- Catalytic reduction method
- Molecular sieve process
- Grande Paroisse process (extended water absorption)
- CDL/Vitok process
- Masar process

All of the above processes have been employed on commercial installations, and all are reportedly capable of meeting the new source performance standard of 3 lb/ton of 100% acid (equivalent to approximately 200 ppm NO_x in the tail gas) for NO_x emissions from nitric acid plants.

In the catalytic reduction process, the tail gas from the nitric acid absorber is heated and passed through a combustor where NO_x is catalytically reduced to N_2 and O_2. Natural gas is used as the fuel in the combustor.

The molecular sieve method is based on the principles of adsorption, oxidation, and regeneration of the sieve. Heat for regeneration is supplied by an oil-fired heater. The process is highly efficient for NO_x removal, generally achieving outlet concentrations below 50 ppm.

In the Grande Paroisse process, the absorber tail gas is sent to a secondary absorber, where it is contacted countercurrently with process water. The additional nitric acid produced in the secondary absorber (from NO_x in the tail gas) is fed to the primary absorber. The NO_x removal in the secondary absorber is sufficient to permit the tail gas to meet Federal standards.

The CDL/Vitok process is similar to the Grande Paroisse process, but the former uses a higher liquid-to-gas ratio and a lower operating temperature. In addition, the nitric acid produced is recycled to the absorber, so that the tail gas is actually scrubbed with nitric acid. The tail gases are thus converted to nitric acid at a concentration that can be commercially utilized.

In the Masar process, the tail gas from the absorber is cooled and then sent to a three-stage absorber. In the first stage, the gas is contacted with chilled feedwater used in the nitric acid absorber. In the second stage, the tail gas is scrubbed with a circulating urea-water solution. In the third stage, the gas is again scrubbed with the feedwater to the nitric acid absorber.

The direct operating energy requirements of the five processes for a 300-ton/day nitric acid plant are presented in Table 31. The catalytic reduction method is by far the most energy-intensive process. The Grande Paroisse is the least energy intensive, requiring 93% less energy than the catalytic reduction process. However, the Grande Paroisse process is capital intensive. The CDL/Vitok process has the lowest capital and operating costs (53).

TABLE 31. DIRECT ENERGY REQUIREMENTS IN NO_x ABATEMENT SYSTEMS FOR A 300-TON/DAY NITRIC ACID PLANT[a] (10^9 Btu/yr)

Energy source	Catalytic reduction	Molecular sieve	Grande Paroisse	CDL/ Vitok	Masar
Steam (credit)	(129.20)	2.04	-[b]	5.83	10.69
Electrical	10.97	27.59	7.71	22.71	1.71
Natural gas	232.56	-	-	-	-
Oil	-	16.32	-	-	-
Total	114.33	45.95	7.71	28.54	12.40
Percent saving over catalytic reduction method	-	60	93	75	89

[a] Data from Reference 53. [b] Dashes indicate that no value is applicable.

INDUSTRIAL PROCESS MODIFICATIONS

From an energy conservation standpoint, the extremely low thermodynamic efficiencies of all flue-gas treatment techniques (Table 13 and Figure 4) emphasize the desirability of reducing pollutant emissions through process modifications rather than by treatment of waste streams whenever possible. One difficulty in dealing with process modifications is that they are highly specific to given processes and are not generally applicable.

The effects on energy requirements of process modifications have been investigated through in-depth studies of a number of industries (41-53, 61-63). The results of these studies are summarized in Table 32. (Process modifications in the iron and steel industry were discussed earlier in this section.)

The results for the Portland cement and olefins industries illustrate the fact that energy requirements for pollution control may

TABLE 32. ENERGY SAVINGS OBTAINABLE BY PROCESS MODIFICATIONS

Industry	Reference number	Energy savings[a], % Pollution control	Total process
Portland cement	48	-48 to 32	0 to 25
Olefins	45	-90 to -40	19 to 22
Copper smelting	62, 63	29	37
Primary aluminum	41	Negligible.	-170 to -84
Cheese making	62, 63	-995 to -556	[b]
Pulp and paper	44	30 to 70	17
Textile	47	20 to 60	50 to 80
Ammonia	46	-34 to -45	3 to 5
Glass	49	-58 to 95	-25 to 21
Chlor-alkali	50	0	27 to 58
Phosphoric acid	51	-1,300 to -130	80 to 84
Petroleum refining	43	98 to 100	0 to 2.3

[a] Negative values represent energy penalties.

[b] Not applicable; the modification involves only the wastewater treatment system.

be increased by a process modification that decreases the overall energy requirement of the process. Factors other than energy, pollution control, and economics may also militate for or against a process modification. In the case of the primary aluminum industry, the factor consists of utilization of domestic versus foreign sources of raw materials.

In the cheese-making industry, the process modification consists of the recovery of whey from the process wastewater. The recovery process involves an evaporative concentration step that is highly energy intensive. However, the recovered whey can be used as a food, and its energy, social, and economic values must be taken into account in judging the utility of the modified process.

The alternative studied in the copper smelting industry is the Noranda continuous smelting process, as opposed to the conventional smelting process. In addition to the reductions in energy consumption idicated in Table 32, use of the Noranda process permits recovery of greater than 90% of the SO_2 in the tail gases compared to 66% recovery with the conventional process (62, 63).

The base case for the Portland cement industry is the oil-fired long kiln. Alternatives studied consist of a suspension preheater, flash calciner, fluidized-bed combustion, and coal-fired long kiln. The suspension preheater and flash calciner both require 32% less energy for pollution control and 25% less energy overall than the oil-fired long kiln. Fluidized-bed consumption requires 48% more energy for pollution control than the long kiln, but 7% less energy overall. The coal-fired long kiln has the same energy requirements as the oil-fired long kiln.

The lower overall energy requirement for the fluidized-bed cement process results from energy recovery from the fluidized-bed reactor off-gas. The entire electrical energy requirement of the plant can be supplied in this manner (48). However, generation of electricity greatly increases the cooling water requirement of the plant. (The additional cooling water is for steam condensation in the powerplant.) The energy requirement for thermal pollution control is correspondingly increased. [(Federal effluent standards for cement plants require the effluent temperature to be no greater than 3°C above the inlet water temperature (48).] The higher pollution control energy requirement for the fluidized-bed cement process is the result of this increased energy requirement for thermal pollution control (48).

The base case selected for the olefins industry is production of ethylene by cracking a 50% ethane/50% propane feed. Two alternative processes are considered--naphtha cracking and gas-oil cracking. Both alternatives require more energy for pollution control and more energy overall per unit weight of ethylene produced. But they both require about 20% less energy overall per unit weight of all products produced. An important consideration in this case, in addition to total energy consumption, is the conservation of scarce raw materials through use of alternative feedstocks (45).

The results listed in Table 32 for the pulp and paper industry are for three alternative pulp manufacturing processes: the standard kraft process (base case), the alkaline-oxygen pulping process, and the Rapson effluent-free kraft process. The pollution control energy requirement in these processes is for wastewater treatment and effluent disposal (44).

In the textile industry, three model knit and woven fabric textile mills employing various advanced processing operations were studied. These model mills were compared with similar baseline mills employing the best techniques currently practiced in the textile industry.

The alternatives studied in the ammonia industry consist of ammonia production from natural gas (base case), ammonia production based on coal gasification, and ammonia production based on heavy oil gasification. The emphasis in this industry is on conservation of natural gas rather than energy savings per se.

In the glass industry, six alternative glass melting processes were studied: natural gas firing (base case), direct coal firing, coal gasification, coal-fired hot gas generation, electric melting, and batch preheating. Only batch preheating has a lower total process energy requirement than the baseline case. Electric melting has the smallest energy requirement for pollution control, but the energy required for pollution control at the powerplant was not included in the calculations. Assuming a 5% energy penalty for pollution control at the powerplant, electric melting requires about the same amount of energy for pollution control as does batch preheating (about 35% less than natural gas firing). However, conservation of natural gas is the primary objective of these process modifications.

The alternatives considered in the chlor-alkali industry include the graphite anode diaphragm cell (base case), the dimensionally stable anode diaphragm cell, and the ion exchange membrane cell. A fourth option, the mercury cell, requires 6% more energy overall than the baseline case and about 20 times as much energy for pollution control. The energy requirements for pollution control in this industry are very small compared with total process energy requirements.

In the phosphoric acid industry, the baseline case is elemental phosphorus production in an electric furnace. The alternative processes consist of the wet process with chemical cleanup of the phosphoric acid and the wet process with solvent extraction cleanup. Although the wet process requires considerably more energy for pollution control than the electric furnace process, this energy is a small fraction of the total process energy.

The process alternatives studied in the petroleum refining industry were:

- Direct combustion of asphalt in process heaters and boilers.
- Hydrocracking of vacuum bottoms.
- Flexicoking of vacuum bottoms.
- Internal electricity generation by burning asphalt.
- Hydrogen generation by partial oxidation of asphalt.

The principal conservation benefit of these options derives from the conversion of refinery residue streams into higher-valued fuels such as refinery gas and distillate-range products.

NONUTILITY COMBUSTION SOURCES

Industrial and commercial boilers constitute a major source of air pollution (Tables 23 and 24). Most of the control methods that have been discussed previously for electric powerplants are also applicable to nonutility combustion sources. Of particular interest are supplementary control systems and fluidized-bed combustion, which have been identified as potentially energy-conserving methods for control of SO_x from utility boilers.

Fuel switching, in combination with tall stacks, is an intermittent control method applicable to nonutility combustion sources. Load shifting, however, is not generally applicable for obvious reasons. As is the case with powerplants, intermittent control of nonutility sources is a strategy for meeting ambient air quality standards. Stricter standards cannot be met by this method, and no significant reductions of atmospheric sulfate levels are achieved.

Fluidized-bed combustion is also applicable to nonutility combustion processes. However, its potential for reducing energy consumption may not be as great in this application. The potentially high thermal efficiency of pressurized fluidized-bed combustion (Table 27) is due in part to the use of a gas turbine to generate electricity from the flue gas. When the objective of the combustion process is the production of process steam rather than electricity, this advantage is lost. Pressurized systems are also more expensive to construct than atmospheric pressure units--a major drawback for small plants. Hence small, industrial, pressurized fluidized-bed boilers may not be economical compared to atmospheric pressure fluidized-bed units (64). The potential energy savings from atmospheric pressure units, compared with flue-gas desulfurization, is considerably less than for pressurized units (Table 27).

Nonenergy aspects of SO_2 control alternatives for nonutility combustion sources are considered in Reference 64. The alternatives are evaluated with respect to the following criteria:

- Pollutant emissions
- Retrofitability
- Operation maintenance
- Capital requirement
- Annualized cost
- Availability

WASTEWATER TREATMENT

The direct operating energy requirements of 11 municipal wastewater treatment methods and 12 sludge disposal techniques were computed in a study by Batelle Memorial Institute (65). The relative energy consumption of the wastewater treatment methods are shown schematically in Figure 7, and the values for the sludge disposal techniques are given in Figure 8. The treatment strategies and sludge options are identified in Tables 33 and 34.

From Figure 8, it is clear that the least energy-intensive sludge options are those that employ sludge thickening and digestion (Options 4 to 8). Methods for handling chemical process sludge (Options 9 to 12) are the most energy intensive, especially those that also employ recalcination and reuse of lime (Options 10 and 12). These comparisons do not include energy required for production of new lime. It is shown in the DSI study (2) that when the

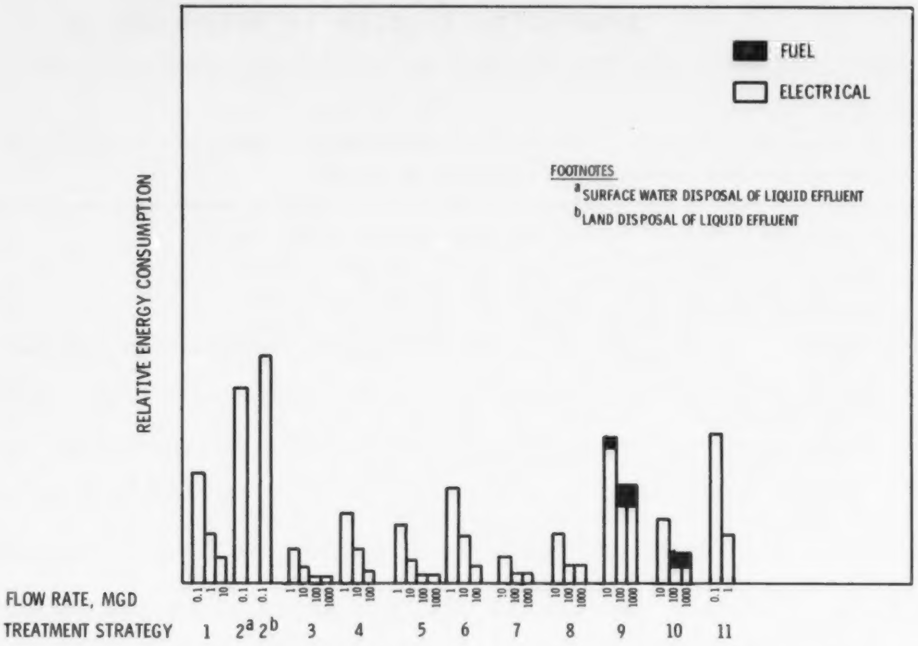

Figure 7. Relative energy consumption per unit capacity of wastewater treatment strategies. (Source: Reference 65)

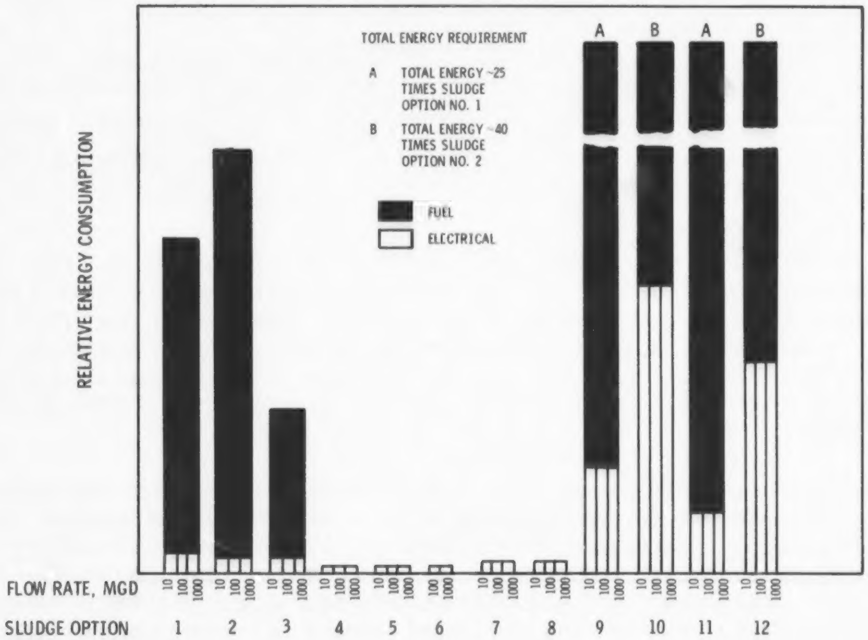

Figure 8. Relative energy consumption per unit capacity of sludge disposal options. (Source: Reference 65)

TABLE 33. SUMMARY OF WASTEWATER TREATMENT STRATEGIES STUDIED IN REFERENCE 65

Wastewater treatment strategy number	Description
1	Primary treatment followed by land application of effluent.
2	Waste stabilization lagoon followed by either spray irrigation or surface water discharge of effluent.
3	Primary and trickling filter treatment with surface water discharge.
4	Primary and trickling filter treatment followed by spray irrigation.
5	Primary and activated sludge treatment with surface water discharge.
6	Primary and activated sludge treatment followed by spray irrigation.
7	Primary and activated sludge treatment with alum addition and nitrification-denitrification followed by surface water discharge.
8	Primary and activated sludge treatment with coagulation-filtration followed by surface water discharge of effluent.
9	Primary and activated sludge treatment, coagulation-filtration, carbon adsorption, and zeolite ammonia removal followed by surface water discharge.
10	Coagulation-filtration and carbon adsorption followed by surface water discharge of effluent.
11	Extended aeration followed by surface water discharge of effluent.

TABLE 34. SUMMARY OF SLUDGE OPTIONS STUDIED IN REFERENCE 65

Sludge option number	Description
1	Sludge thickening, chemical conditioning by polymers, vacuum fultration, incineration, and landfill.
2	Chemical conditioning by polymers, centrifugal dewatering, incineration, and landfill.
3	Sludge thickening, conditioning by heat treatment, vacuum filtration, incineration, and landfill.
4	Sludge thickening, digestion, sand drying, and landfill.
5	Sludge thickening, digestion, and land spreading.
6	Sludge thickening, digestion, and ocean dumping by pipeline.
7	Sludge thickening, digestion, chemical conditioning, vacuum filtration, and landfill.
8	Sludge thickening, digestion, chemical conditioning, vacuum filtration, and ocean dumping by barging.
9	Chemical sludge thickening, vacuum filtration, incineration, and landfill.
10	Chemical sludge thickening, vacuum filtration, recalcination and reuse, and landfill of wasted residue.
11	Chemical sludge thickening, centrifugal dewatering, incineration, and landfill.
12	Chemical sludge thickening, centrifugal dewatering, recalcination and reuse, and landfill of wasted residue.

energy credit for new lime production is included in the calculations, recalcination and reuse of lime (Options 10 and 12) is still more energy intensive than sludge incineration (Options 9 and 11). However, the difference in energy requirements between the two options (recalcination and reuse versus incineration) is only about one-half as great when the energy for lime production is included.

The energy consumption of the wastewater treatment methods is strongly dependent on the plant size, which makes comparisons more difficult. However, Strategy 3, trickling filter treatment with surface water discharge, appears to be the least energy intensive. Strategy 5 (activated sludge with surface water discharge) and Strategy 7 (biological-chemical treatment) also have relatively low energy requirements. Not surprisingly, tertiary treatment (Strategy 9) is the most energy intensive. (Of course, tertiary treatment has a correspondingly high contaminant removal efficiency.)

The difference in total energy requirements between activated sludge and trickling filter treatment can be considerable. In one example (68), calculations were made for a 1-million-gal/day treatment plant. The total (direct and indirect operating energy and capitalization energy) energy requirement for the trickling filter plant was about one-half the requirement for the activated sludge plant. Data of Smith (28) show that electrical energy consumption in trickling filter plants is 64% of that in activated sludge plants at the 1-million-gal/day plant size, 55% at the 10-million-gal/day size, and 50% at the 100-million-gal/day size.

Trickling filter plants generally have somewhat lower removal efficiencies for BOD (biological oxygen demand) than do activated sludge plants. However, trickling filter plants designed for effluent recycle can achieve removal efficiencies equivalent to activated sludge plants. Disadvantages of trickling filter plants relative to activated sludge plants include lower adaptability to changes in wastewater pH, organic matter content and temperature, and higher capital investment costs.

Significant energy savings are possible through utilization of the gas produced by anaerobic digestion of organic sludge. For example, sludge digester gas can be used to fuel internal combustion engines, which can be directly coupled to air blowers and water pumps; or it can be used to drive electrical generators. Smith (28) estimates that essentially all of the electrical energy required by primary treatment plants could be obtained in this manner. For activated sludge plants, approximately two-thirds of the electricity requirements could be supplied by digester gas (28).

An alternative method to anaerobic sludge digestion as a method of energy recovery from sludge is dewatering (an energy consuming step) followed by incineration of raw sludge. A waste heat boiler can be used to recover energy from the incinerator exhaust gas. The steam may be used to supply process and building heat and/or to generate electricity. Smith (67) has found that under the most ideal conditions, this method is competitive with anaerobic digestion on a power recovery basis. But the disadvantage to anaerobic digestion is that considerable sludge solids remain after digestion, and the solids require dewatering and ultimate disposal. The energy required for dewatering and disposal of this residual sludge was not included in the above comparison.

For advanced wastewater treatment using activated carbon, organic solvents can be used to regenerate the carbon as an alternative to thermal regeneration. It is estimated that solvent regeneration may require only one-tenth the energy needed for thermal regeneration (68).

For the concentration of wastewater streams, reverse osmosis, electrodialysis, and vapor compression evaporation are less energy intensive alternatives to standard multi-effect evaporation (68).

ENERGY RECOVERY FROM MUNICIPAL SOLID WASTE

Energy recovery efficiencies of a number of processes for recovering energy from solid waste are given in Reference 69 and are reproduced in Table 35. The first column of the table lists the net energy recovered as fuel, which is reported as a percentage of the heat value of the solid waste input to the process. This value is multiplied by the boiler efficiency to obtain the percentage of input solid waste energy available as steam to the consumer. On the basis of the latter values, the waterwall incinerator, the dust RDF process, the Purox gasifier, and the Torrax gasifier have the highest recovery efficiencies.

TABLE 35. ENERGY RECOVERY EFFICIENCIES OF SOLID WASTE ENERGY RECOVERY PROCESSES[a]

	Energy recovered, percent of solid waste heat value	
Process	Net fuel produced	Total energy available as steam
Waterwall incinerator	-[b]	59
Fluff RDF[c]	70	49
Dust RDF[c]	80	63
Wet RDF[c]	76	48
Purox gasifier	64	58
Monsanto gasifier	78	42
Torrax gasifier	84	58
Oxy pyrolysis	26	23
Biological gasification:		
With use of residue	29	42
Without use of residue	16	14
Brayton cycle	31.7[d]	-[b]

[a] Data from Reference 69. [b] Not applicable.

[c] Refuse-derived fuel. [d] 12.3 as electricity plus 19.4 as steam.

A caveat is in order regarding the data listed in Table 35. The efficiencies are based on energy balances performed on each process in Reference 69. Since most of the processes have not been operated on a commercial scale, the data on which the energy balances are based are of questionable validity. In addition, the energy value of recovered materials is not included in the analysis. For example, the Monsanto LANDGARD® system is designed to recover glassy aggregate and ferrous metals for sale and reuse.

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APPENDIX A

OVERVIEW OF PREVIOUS WORK

An overview of the literature survey is presented in this section. Each article that made a significant contribution to the data base is briefly reviewed. Details of the results and the methods employed are presented in Section 4. The list of articles is not exhaustive, but all of the major work in this area is included. A number of the articles are in the form of draft reports that are subject to revision; these reports are so noted.

The literature reviewed is divided into three categories: broad-scope studies, in-depth studies, and other related work. Articles that cover all or many sectors of the economy (but in necessarily limited detail) are classified as broad-scope studies. The intent of these studies is normally to provide an overall picture of the energy required for pollution control on the national level. By contrast, studies that cover only one or several industries in considerable detail are classified as in-depth studies. In some cases where the distinction between the two categories is not entirely clear, the classification is based on the level of detail employed in the study. Articles that do not fit in either of the above categories, but that contain information pertinent to the present work, are classified as "other related work."

BROAD-SCOPE STUDIES

DSI, Draft Report, 1975 (2)

This is the most definitive of the broad-scope studies. Incremental energy requirements are estimated for pollution control to meet Federal regulations in 1977 and 1983 for major stationary source sectors. These sectors are:

- Power plant thermal and air pollution control
- Municipal wastewater treatment
- Industrial water and air pollution control

Average values of energy consumption per unit of capacity are used with estimates of the capacity requiring control. The latter are generally estimates made by EPA. Calculations for the industrial sector are based on estimates of incremental investment in pollution control equipment made by the Council on Environmental Quality. Indirect energy for chemicals and sludge disposal is included where data permit. Energy for the fabrication and installation of pollution control equipment is estimated using results from energy input/output analysis (26, 27).

Major assumptions made in each calculation are clearly stated; however, data sources are not always well-documented, which hinders the evaluation of results. In addition, the results are in terms of incremental energy requirements relative to a moving baseline that is not explicitly described in the report. Hence, estimation of total energy required for pollution control is difficult.

EEI (Edison Electric Institute), 1972 (22)

Results of a 1972 survey of 87 electric utilities made by the Edison Electric Institute are reported. Total electrical energy consumption for pollution control in the industrial sector is given for 1971 according to the 2-digit standard industrial classification (SIC) code. Projected annual electrical energy consumption for pollution control for the period 1973-77 is presented for each industrial SIC class.

Values of electrical energy consumption for sewage treatment plants are also given.

Data from this survey represent the most comprehensive estimates available for pollution control energy consumption in the industrial sector. However, only electrical energy is included, and it is not broken down into water, air, and solid waste pollution control. In addition, the projections are for actual energy consumption, not energy required to meet all Federal standards. The survey covered utility companies whose sales accounted for approximately 20% of total national electrical energy sales to industrial customers.

Michigan, 1975 (4)

This study was performed at the University of Michigan as part of the Energy Policy Project sponsored by the Ford Foundation. The project is similar in scope and methodology to the DSI study, which it predates. However, most of the estimates of energy requirements for pollution control are given for 1985 only. Considerable original work was performed, particularly in obtaining unit energy requirements for various control strategies. A number of these values have been used in subsequent studies.

Hirst, 1973 (8)

Analyses in this study are less detailed and less consistent than the DSI and Michigan studies. Areas covered are:

- Mass transit
- Automotive controls
- Wastewater treatment
- Solid waste management (including disposal, recycling, and energy recovery)
- Air pollution
- Thermal pollution
- Energy conservation

Calculations are based on 1970 data with stringent (but arbitrary) levels of control assumed. Only direct operating energy for pollution control equipment is considered. The results of this study have been published in a number of different articles, all of which contain essentially the same information (70-73).

RPA, 1974 (5)

This study considers the effects of environmental legislation on energy supply and demand. Increased energy demand as a result of pollution control legislation is estimated for 1973 and 1980 in five sectors:

- Stationary sources of air pollution
- Mobile sources
- Lead restrictions for gasoline
- Water quality standards for both thermal and waste content
- Municipal solid waste management

The calculation for SO_x control at powerplants is similar to that of the DSI and Michigan studies. Little or no detail is given of the other stationary source estimates.

Cywin, 1975 (6)

This brief article deals primarily with energy requirements for water pollution control, but estimates are also given for air pollution control, control of mobile sources, and solid waste programs. Estimates of energy required to meet EPA regulations are given for 1980. For water pollution control, the major assumptions are outlined, but details of the calculations are not given. Results for the other sectors are based on EPA estimates or estimates furnished by government contractors, but the methodology is not given. Only direct energy requirements are considered. EPA is said to believe that the estimates given in this article are conservative (i.e., near the upper limit for energy requirements) because of the following underlying assumptions:

- No new technologies are used that would be more energy efficient than those currently in use.

- Energy prices are low (pre-embargo level) so that the incentive to reduce energy consumption is minimal.

- There is no explicit Federal energy conservation program.

Bendixen and Huffman, 1974 (17)

Energy requirements for several pollution control strategies are estimated and compared with energy consumption in other sectors of the economy. Direct energy required for SO_x scrubbers on powerplants is estimated for 1974 assuming the total national capacity uses 3.5% sulfur coal and is equipped with scrubbers. Electrical energy consumption for municipal wastewater treatment in 1974 is estimated using 1968 data given by Smith (28) and assuming that the total population is served by tertiary treatment. Energy associated with solid waste collection and disposal is quoted from Hirst (71).

IN-DEPTH STUDIES

ERT, 1977 (3)

Energy requirements for pollution control are studied for the fossil fuel steam electric power industry. Unit energy requirements (including preplant, inplant, and postplant uses) are obtained from the literature for various pollution control strategies. The most frequently cited references are EPA publications and the Michigan study (4). The capacity requiring control is calculated for compliance with various Federal and State regulations in 1983. The distribution of generating capacity, by size, region, and fuel type is obtained by projecting data for the baseline year 1974 to 1983. These data are obtained from the FEA survey of 100 powerplants together with a supplementary survey made by ERT to determine energy use for pollution control. Dispersion modeling is used to determine capacity requiring control to meet ambient air quality standards. Energy requirements are computed for seven different SO_x control strategies and attainment of five different air quality goals. Energy requirements for control of particulate matter and thermal pollution are also given.

Iron and Steel, 1976 (40)

A detailed materials-flow approach based on industry-supplied data is used to estimate pollution control energy requirements. The steel-making process is broken down into unit processes that are analyzed individually for pollution control energy needs. A representative (average) size for each unit is determined based on industry data, and the pollution control methods required to meet standards are identified. Energy consumption data for individual pollution control methods are then used to find pollution control energy requirements for each unit process. Total industry pollution control energy requirements are obtained by multiplying unit process values by the number of plants using each type of unit process. Energy requirements are based on 1972 production data, but estimates for 1977 and 1983 are also included.

Energy requirements are given for inplant air pollution control, inplant water pollution control, and preplant and postplant pollution control activities. The preplant energy includes indirect energy for fabrication of equipment and chemicals as well as energy used for pollution control by electric utilities in supplying the additional electricity required by steel plants. The energy values given are those required to meet all State and Federal regulations in 1983. Calculations are also made assuming less stringent regulations. Pollution control energy savings obtainable by modifications of unit processes and pollution control systems are also presented.

Temple, Barker, and Sloane, 1976 (7)

A detailed analysis of the effects of pollution control regulations on electric powerplants is presented. Most of the results are given in economic terms. National energy penalties for cooling towers, scrubbers, and electrostatic precipitators are given for 1980 and 1985. No details of the estimation procedures are given.

A. D. Little, 1976 (41-53)

Detailed analyses of 13 selected industries are given emphasizing environmental aspects of potential energy-conserving process modifications. Both total energy requirements and energy requirements for pollution control in alternative processes are considered. In one case, nitric acid plants (53), energy requirements for alternative pollution control methods are given.

DSI, Draft Reports, 1975 (62, 63)

The effects of process modifications on the energy required for pollution control are studied in four selected industries: copper smelting, pulp and paper bleach plants, potato processing, and cheese making. Only the copper and cheese-making reports were available for use in the present study. A detailed materials-flow approach is employed to determine the energy requirements for alternative processes. For copper smelting, the energy required to operate an acid plant for SO_x control is determined for a traditional smelting process and for the Noranda process. For cheese making, the alternatives consist of recovery of whey from the watewater versus treatment of the wastewater without recovery of whey.

Smith, 1973 (28)

In this widely-quoted work, electric power consumption is computed for unit processes employed in primary, secondary, and tertiary wastewater treatment. These unit energy consumption values are then combined to calculate the electrical energy requirements of alternative wastewater treatment strategies. Energy requirements for fuel and chemicals are not considered.

Mills and Tchobanoglous, 1975 (66)

This work deals with energy requirements for municipal wastewater treatment. It is similar in scope to, and largely based upon, the work of Smith (28). However, energy requirements for fuel, chemicals, and capital equipment are also taken into account. The latter are obtained from energy input/output analysis (26, 27). Energy consumption data for unit processes are conveniently tabulated for easy reference. Energy requirements for two alternative wastewater treatment schemes are calculated as an example.

NCWQ, Draft Report, 1975 (10)

This voluminous report discusses the economic, social, and environmental impacts associated with the 1972 Federal Water Pollution Control Act Amendments. Of interest in the present context are estimates of the energy requirements for municipal and industrial wastewater treatment and powerplant thermal pollution control. The energy estimate for municipal wastewater treatment is based on data from the 1974 EPA needs survey. In-depth studies were made of powerplants and 10 other selected industries:

- Canned and preserved fruits and vegetables
- Inorganic chemicals
- Iron and steel
- Metal finishing
- Organic chemicals
- Petroleum refining
- Plastics and synthetics
- Pulp and paper
- Textiles
- Feedlots

All other industries were lumped together, and their energy requirements were estimated based on total operating and maintenance costs. Although few details of the individual studies are given, it can be surmised from the breadth of the above industrial categories that the analyses were of limited depth.

BMI, 1974 (65)

Energy requirements are given for 11 different municipal wastewater treatment schemes and 12 different sludge disposal methods. Only direct operating energy is considered. The treatment methods and sludge disposal methods are treated separately. The study is not primarily concerned with energy requirements, and other design parameters are also given for each method. The assumptions that form the basis for the design calculations are outlined, but no details of the calculations are given.

Solid Waste, 1976 (69)

Energy balances are presented for a number of processes for recovering energy from municipal solid waste. Energy recovery efficiencies are given for each process based on the energy balance calculations. Many of the data for the energy balances are from reports made by companies developing the various processes, most of which have not been operated on a commercial scale. Hence the validity of the data on which the calculations are based is open to question.

Iron and Steel Institute, 1976 (61)

Fifteen different process modifications that have been proposed as energy conservation measures in the iron and steel industry are analyzed. The advantages and disadvantages of each proposed modification are given. Factors considered in the analyses include technical aspects, economic aspects, environmental effects, potential energy savings, and effect on product quality.

OTHER RELATED WORK

Batelle, Draft Report, 1975 (38)

This report compiles economic, operational, and pollution data on 91 selected four-digit SIC industries. Data obtained from literature sources are tabulated on the following parameters:

- Major pollutants
- Annual production
- Dollar value of production
- Ability to pass on costs
- Financial dispersion
- Geographical dispersion
- Research capabilities
- Water discharge
- Energy consumption
- Recycled materials

Of interest in the present study is an extrapolated tabulation of the EEI (22) data on electrical energy consumption for pollution control. The EEI two-digit classification is resolved to four digits by apportioning the pollution control energy according to the percentage of total energy consumption for each four-digit class. The fact that the EEI survey data represent only about 20% of total electric sales to industrial customers is not mentioned, and the reader is led to believe that the data represent total industrial energy consumption for pollution control.

Economics of Clean Water, 1973 (9)

This report is the sixth in a series of reports to the Congress by EPA as required by the Federal Water Pollution Control Act. Municipal, industrial, and electric utility wastewater and thermal discharges are covered. Estimates of capital and operating costs to meet 1977 standards are given. Direct energy requirements for powerplant thermal pollution control are given for 1977 and 1983. However, no information on the source of these estimates is given.

MacDonald, 1975 (16)

The environmental, energy, and economic penalties associated with three SO_x control strategies for coal-fired electric powerplants are investigated. The three strategies are:

- To achieve State implementation plan requirements by burning low-sulfur western coal.
- To achieve State implementation plan requirements by burning high-sulfur coal and installing limestone scrubbers to remove SO_2 from the flue gas.
- To meet ambient air quality standards by burning high-sulfur coal and employing supplementary control systems.

National energy requirements for each strategy are calculated by a unique method based on an estimate by the Federal Energy Office of the 1975 fuel deficit that would have resulted from enforcement of existing State implementation plans with no switching from coal to gas or oil.

Stukel and Rigo, 1975 (33)

The energy efficiencies of particulate and SO_x control devices are calculated. The efficiency is defined as the ratio of the minimum reversible energy required to separate the pollutant from a gas stream to the actual energy required. The minimum energy is calculated as the sum of the kinetic energy of the pollutant and the reversible energy of mixing.

Hittman, 1974 (74)

A computerized data base is developed for pollutant emissions associated with various energy supply and end use activities. Energy supply activities include coal supply, oil supply, natural gas supply, and electric powerplants. End us activities include residential, commercial, industrial, and transportation uses. For each activity, environmental impact tables are presented that give pollutant emissions associated with each aspect of the given activity. The footnotes to the table for electric powerplants contain some unit energy consumption figures for pollution control. These are the only data that have a direct bearing on the present study.

Rochelle, 1973 (19)

Unit power and fuel requirements of a number of SO_x control systems are given as a percentage of powerplant output. Included are throwaway and regenerable scrubbing methods and dry processes. The source of the data is not given, but it reportedly was based in part on then-current results of several large-scale EPA demonstration projects.

APPENDIX B

RANKING OF INDUSTRIAL SECTOR BY FOUR-DIGIT SIC CATEGORIES

TABLE B-1. RANKING OF EEI (2) DATA BASED ON BATELLE RESOLUTION TO FOUR-DIGIT SIC CATEGORIES[a]

SIC	Name	Rank	Percent of total[b]	Cumulative percent
3312	Blast furnaces and steel mills	1	22.54	22.54
2911	Petroleum refining	2	8.46	31.00
2621	Papermills	3	6.03	37.03
2869	Industrial organic chemicals, NEC	4	5.31	42.34
2631	Paperboard mills	5	4.74	47.08
3662	Radio and TV commercial equipment	6	3.43	50.51
2819	Industrial inorganic chemicals, NEC	7	3.29	53.80
3334	Primary aluminum	8	2.57	56.37
3621	Motors and generators	9	2.54	58.91
3462	Metal forgings and stampings	10	1.69	60.60
3321	Gray iron foundries	11	1.52	62.12
3714	Motor vehicle parts and accessories	12	1.39	63.51
3352	Aluminum rolling and drawing	13	1.29	64.80
3711	Motor vehicles	14	1.26	66.06
3331	Primary copper	15	1.20	67.26
2895	Carbon black	16	1.17	68.43
3465	Automotive metal stampings	17	1.15	69.58
3691	Storage batteries	18	1.06	70.64
3313	Electrometallurgical products	19	1.00	71.64
12--	Coal and lignite mining	20	0.94	72.58
2611	Pulp mills	21	0.93	73.51
2812	Alkalies and chlorine	22	0.92	74.43
3471	Plating and polishing	23	0.86	75.29
2821	Plastic materials and resins	24	0.85	76.14
3391	Iron and steel forgings	25	0.83	76.97
2824	Organic fibers, noncellulosic	26	0.81	77.78
3333	Primary zinc	27	0.76	78.54
2865	Cyclic intermediates and crudes	28	0.75	79.29
3531	Construction machinery	29	0.74	80.03
3523	Farm machinery	30	0.67	80.70
3996	Hard surface floor coverings	31	0.66	81.36

See footnotes at end of table, p. 90.

(continued)

TABLE B-1 (continued)

SIC	Name	Rank	Percent of total[b]	Cumulative percent
3469	Metal stampings, NEC	32	0.55	81.91
3914	Silverware and plated wares	33	0.55	82.46
3399	Primary metal products, NEC	34	0.54	83.00
3323	Steel foundries	35	0.52	83.52
3221	Glass containers	36	0.49	84.01
3351	Copper rolling and drawing	37	0.47	84.48
2661	Building paper and board mills	38	0.46	84.94
3341	Secondary nonferrous metals	39	0.46	85.40
2823	Cellulosic manmade fibers	40	0.45	85.85
2653	Corrugated and solid fiber boxes	41	0.40	86.25
2813	Industrial gases	42	0.39	86.64
3361	Aluminum castings	43	0.39	87.03
3721	Aircraft	44	0.37	87.40
242-	Sawmills and planing mills	45	0.36	87.76
2822	Synthetic rubber	46	0.36	88.12
3724	Aircraft engines and parts	47	0.33	88.45
3322	Malleable iron foundries	48	0.31	88.76
3357	Nonferrous wiredrawing, insulating	49	0.31	89.07
2816	Inorganic pigments	50	0.29	89.36
3079	Miscellaneous plastic products	51	0.29	89.65
3273	Ready-mix concrete	52	0.29	89.94
3251	Brick and structural tile	53	0.27	90.21
3011	Tires and innertubes	54	0.27	90.48
2899	Chemical preparations, NEC	55	0.26	90.74
2011	Meatpacking plants	56	0.25	90.99
2873	Nitrogen fertilizers	57	0.25	91.24
3316	Cold finishing of steel shapes	58	0.24	91.48
3332	Primary lead	59	0.24	91.72
3229	Pressed and blown glass	60	0.23	91.95
3315	Steel wire and related products	61	0.23	92.18
2013	Sausages and other prepared meats	62	0.23	92.41
2063	Beet sugar	63	0.23	92.64
3317	Steel pipes and tubes	64	0.21	92.85
3339	Primary nonferrous metals, NEC	65	0.21	93.06
2951	Paving mixtures and blocks	66	0.21	93.27
2834	Pharmaceutical preparations	67	0.21	93.48
249-	Miscellaneous wood products	68	0.21	93.69
3211	Flat glass	69	0.20	93.89
3356	Nonferrous rolling and drawing, NEC	70	0.20	94.09
3511	Steam engines and turbines	71	0.19	94.28
2221	Weaving mills, manmade fibers	72	0.18	94.46
243-	Millwork, plywood, related products	73	0.18	94.64
3731	Shipbuilding and repair	74	0.18	94.82
2211	Weaving mills, cotton	75	0.18	95.00

See footnotes at end of table, p. 90.

(continued)

TABLE B-1 (continued)

SIC	Name	Rank	Percent of total[b]	Cumulative percent
3069	Fabricated rubber products	76	0.18	95.18
2046	Wet corn milling, etc.	77	0.18	95.36
14--	Mining, nonmetallic minerals	78	0.17	95.53
3392	Nonferrous forgings	79	0.17	95.70
2841	Soaps and other detergents	80	0.16	95.86
2892	Explosives	81	0.16	96.02
13--	Oil and gas extraction	82	0.15	96.17
3296	Mineral wool	83	0.15	96.32
2262	Finishing mills, synthetics	84	0.15	96.47
2048	Prepared feeds	85	0.15	96.62
2511	Wood household furniture	86	0.15	96.77
2026	Fluid milk	87	0.15	96.92
2033	Canned fruits and vegetables	88	0.15	97.07
2051	Bread, cake, and related products	89	0.14	97.21
2833	Medicinals and botanicals	90	0.14	97.35
2082	Malt liquors	91	0.13	97.48
2261	Finishing mills, cotton	92	0.13	97.61
3369	Nonferrous castings, NEC	93	0.13	97.74
2075	Soy bean oil mills	94	0.12	97.86
2851	Paints and varnishes	95	0.11	97.97
3295	Minerals ground and treated	96	0.11	98.08
3362	Brass, bronze, and copper castings	97	0.11	98.19
2077	Animal and marine fats and oils	98	0.10	98.29
2062	Cane sugar refining	99	0.10	98.39
2711	Newspapers	100	0.09	98.48
2037	Frozen fruits and vegetables	101	0.09	98.57
99--	Nonclassifiable	102	0.08	98.65
2879	Pesticides, etc.	103	0.07	98.72
3466	Crowns and closures	104	0.07	98.79
2023	Condensed and evaporated milk	105	0.06	98.85
2085	Distilled liquors; example: brandy	106	0.06	98.91
2861	Gum and wood chemicals	107	0.05	98.96
2015	Poultry dressing plants	108	0.05	99.01
2752	Commercial printing, lithographies	109	0.05	99.06
10--	Metal mining	110	0.05	99.11
2061	Raw cane sugar	111	0.04	99.15
23--	Apparel and related products	112	0.04	99.19
3861	Photographic equipment adn supplies	113	0.04	99.23
2022	Cheese, natural and processed	114	0.03	99.26
2021	Creamery butter	115	0.03	99.29
21--	Tobacco manufactures	116	0.02	99.31
3111	Leather tanning and finishing	117	0.02	99.33
19--	Ordnances and accessories	118	0.02	99.35
244-	Wooden containers	119	0.01	99.36

See footnotes at end of table, p. 90.

(continued)

TABLE B-1 (continued)

SIC	Name	Rank	Percent of total[b]	Cumulative percent
2017	Poultry and egg processing	120	0.01	99.37
3811	Engineering and scientific instruments	121	0.01	99.38
59--	Retail stores	122	0.00	99.38
01--	Agriculture	123	0.00	99.38
2091	Canned and preserved seafoods	124	0.00	99.38
2411	Logging camps and contractors	125	0.00	99.38
5171	Petroleum bulk stations and terminals	126	0.00	99.38

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[a] Reference 38 is a draft report subject to revision.

[b] Percent 1977 energy requirement for pollution control in industrial sector.